Forest Research Information Paper 166

Forest Soil and Water Research Program:

Five-Year Research Strategy 2006-2011

Ontario

Ontario Forest Research Institute
OFRI · IRFO

Forest Research Information Paper No. 166

Forest Soil and Water Research Program:

Five-Year Research Strategy 2006-2011

Jim McLaughlin

Ontario Forest Research Institute
Ontario Ministry of Natural Resources
1235 Queen Street East
Sault Ste. Marie, Ontario
Canada P6A 2E5

2007

APPLIED RESEARCH AND DEVELOPMENT • ONTARIO MINISTRY OF NATURAL RESOURCES

2007-05547/

Library and Archives Canada Cataloguing in Publication Data

McLaughlin, Jim W.
Forest soil and water research program : five-year research strategy 2006-2011

(Forest research information paper, ISSN 0319-9118 ; no. 166)
Includes bibliographical references.
Available also on the Internet.
ISBN 978-1-4249-4039-4

1. Forest soils—Research—Ontario.
2. Hydrology, Forest—Research—Ontario.
3. Forest ecology—Research—Ontario.
4. Ontario. Forest Soil and Water Research Program.
I. Ontario Forest Research Institute.
II. Title.
III. Series.

SD356.54.C2 M35 2007 631.4072'0713 C2007-964002-8

© 2007, Queen's Printer for Ontario
Printed in Ontario, Canada

Single copies of this publication are available from:

Ontario Forest Research Institute
Ministry of Natural Resources
1235 Queen Street East
Sault Ste. Marie, ON
Canada P6A 2E5

Cette publication hautement spécialisée *Forest Soil and Water Research Program: Five-Year Research Strategy 2006-2011* n'est disponible qu'en anglais en vertu du Règlement 411/97, qui en exempte l'application de la Loi sur les services en français. Pour obtenir de l'aide en français, veuillez communiquer avec le ministère de Richesses naturelles au (705) 946-2981

This paper contains recycled materials.

Abstract

This report presents a five-year research strategy for MNR's Forest Research and Development Section's Forest Soil and Water Research Program (FSWRP). Included are the program's goals, research priorities, policy links, transfer plans, staffing needs, and partnerships. The FSWRP contributes to MNR's policy support using three major research themes: (1) riparian zone management, (2) silviculture and soils, and (3) climate change; all areas that the program has been addressing since 2002 and in which knowledge uncertainty is high. Planned 2006-2011 research efforts will continue to reduce uncertainties, specifically in relation to soil carbon and water cycling. Also, partnerships will be refined to address emerging issues such as peatland management (under the climate change theme) as well as to parameterize and validate a series of process-based carbon, nutrient, and water models to improve understanding of how soil carbon and water interactions affect forest and aquatic productivity to develop a measurable indicator for sustainable forest management. This five-year strategy is based on a synthesis of the results of a workshop titled *Integrating OMNR Research Priorities and Climate Change: Soil and Water Resources* held February 15 – 16, 2005 in Sault Ste. Marie, as well as new policy directions introduced since that workshop.

Resumé

Programme de recherche sur les sols forestiers et l'eau : plan quinquennal (de 2006 à 2011)

Le rapport présente le plan quinquennal des travaux de recherche associés au Programme de recherche sur les sols forestiers et l'eau (PRSFE), mis en œuvre par la Section de la recherche-développement forestière (ministère des Richesses naturelles). On y trouve une description des objectifs du programme, des priorités en matière de recherche, des plans de transfert, des partenariats et des besoins en fait de personnel, ainsi que des liens vers les pages Web qui renferment les politiques pertinentes. Le programme aide le MRN à remplir sa mission en se concentrant sur trois grands domaines de recherche : 1) gestion des zones riveraines; 2) sylviculture et sols; 3) changement climatique. Ce sont tous des sujets abordés par le programme depuis 2002 et dont les connaissances sont très lacunaires. Les travaux de recherche prévus pour la période quinquennale de 2006 à 2011 permettront de réduire les incertitudes, particulièrement en ce qui concerne la teneur en carbone des sols et le cycle de l'eau. En outre, les partenariats seront perfectionnés, afin d'aborder des questions qui se dessinent, telle la gestion des tourbières (sous le thème du changement climatique), et de définir les paramètres et de valider un ensemble de modèles pour la modélisation du carbone, des substances nutritives et de l'eau dans les sols. On pourra ainsi mieux comprendre la façon dont les interactions entre le carbone et l'eau des sols se répercutent sur la productivité des milieux forestier et aquatique, ce qui permettra de concevoir un indicateur mesurable pour l'aménagement forestier durable. Le plan quinquennal repose sur la synthèse des résultats d'un atelier (*Integrating OMNR Research Priorities and Climate Change: Soil and Water Resources*) qui a eu lieu les 15 et 16 février 2005, à Sault Ste. Marie. Il repose également sur les nouveaux principes directeurs qui ont été instaurés depuis l'atelier.

Acknowledgements

Support for this project was provided by the Ontario Forest Research Institute (OFRI) and the Ontario Ministry of Natural Resources (OMNR) under the auspices of CC-167. The author also thanks Lisa Buse of OFRI's Technology Transfer Department for reviewing and putting together the manuscript for publication. Thanks are also given to Sandra Wawryszyn of OFRI for help in preparing tables and figures and reviewing drafts. Thanks also to Paul Gray, Senior Policy Advisor for OMNR's Applied Research and Development Branch; Jenny Gleeson, Alternative Energy Program Officer OMNR's Renewable Energy Section, Lands and Waters Branch; Dr. Nathan Basiliko of the University of Toronto at Mississauga; and Dr. Barry Warner of the University of Waterloo, for useful comments on the report. Finally, thanks to all participants of the *Integrating OMNR Research Priorities and Climate Change: Soil and Water Resources Workshop* for their thoughtful suggestions and recommendations for the Forest Soil and Water Research Program.

Contents

Abstract i

Resumé i

Acknowledgements ii

Executive Summary v

Program Goals 1

Research Hypothesis and Conceptual Framework 1

Policy Directions 3

2006-2011 Research Direction 5

Research Program 6

- Riparian Zone Management 7
- Silviculture and Soils 12
- Climate Change 15

Partnerships 20

Staffing 23

Program Development and Future Initiatives 24

Technology Transfer 24

Program Funding and Challenges 25

Literature Cited 26

Appendix I 31

Appendix II 35

Executive Summary

Forest policy drivers and management approaches are rapidly evolving at international, national, and provincial levels. In the past few years multiple decisions have been made at all jurisdictional levels that will have important implications for forest management and related research on Crown land in Ontario. At the provincial level, the Ontario Ministry of Natural Resources (OMNR) recently published two documents (1) *Our Sustainable Future*, which establishes the framework for sustainable management in Ontario (OMNR 2005a) and (2) *Science for Our Sustainable Future: A Science Strategy for the OMNR* (OMNR 2005b), which provides the framework that OMNR's science organization will use to address priorities set out in the former document. Also, in March 2006 OMNR's Executive Committee directed the preparation of a framework for policy development on peat.

In addition to provincial strategies, international agreements, such as the Kyoto Protocol and the United Nations Economic Commission for Europe (UNECE) Convention on Long-Range Transboundary Air Pollution (LRTAP) will also influence management decisions at the provincial level. The latter agreement requires signatory countries to report on critical loads of acidity and their exceedances for forest soil and aquatic ecosystems. The 2004 Canada-wide acid rain report (Environment Canada 2004) indicated that 45 million hectares of Ontario forest land are currently exceeding acidity critical loads or are near their threshold levels. The rapid evolution in policy and international commitments requires that OMNR be more effectively linked to national and international policy initiatives and research priorities to address current and emerging sustainable natural resource management issues.

OMNR's Forest Research and Development Section's (FRDS) Forest Soil and Water Research Program (FSWRP) is aligned with emerging OMNR research priorities as well as existing OMNR strategies and legal documents including: (1) Science Support for Enhanced Forest Productivity and Mitigating Wood Supply Shortfalls, (2) the Ontario Forest Accord, (3) Ontario's Living Legacy Land Use Strategy, and (4) Climate Change and MNR: A Strategy and Action. Moreover, three new elements have been added to the *2006 State of the Forest Report*'s Global Ecological Cycles criterion: (1) *Monitoring Forest Production of Nitrous Oxide* (4.3.1), (2) *Monitoring Acid Rain Deposition* (4.3.2), and (3) *Monitoring Evapotranspiration* (4.4.1). The FSWRP contributed significantly to the development of these elements in partnership with the OMNR's Forest Management Branch (FMB) and will continue to provide related supporting data. OMNR is also currently developing a stand-level forest management guide that will consider hydrological responses of forest disturbance and their effects on aquatic ecosystems about which current understanding is rudimentary. A key link among all the above policy issues is the interaction between forest soil carbon cycling and hydrology and their regulation of terrestrial and aquatic productivity. Soil carbon and hydrological processes in Ontario's forests are, however, highly uncertain.

The FSWRP contributes to scientific policy support using three major research themes: (1) riparian zone management, (2) silviculture and soils, and (3) climate change. High uncertainty exists for each of the above themes, which the program has been addressing since 2002. Planned 2006-2011 research efforts will continue to further reduce uncertainties around soil carbon and water cycling. As well, partnerships will be refined to address emerging issues such as peatland management (under the climate change theme) as well as to parameterize and validate a series of process-based carbon, nutrient, and water models to improve understanding of how soil carbon and water interactions affect forest and aquatic productivity to develop a measurable indicator for sustainable forest management.

The FSWRP is directly linked to various national and international research networks and programs, such as the National Aquatic Systems and Climate Change Research Network (NASCC-RN), Fluxnet-Canada (e.g., Canadian Carbon Program), the Sustainable Forest Management Network (SFMN), and BIOCAP Foundation. This allows program staff to remain on the forefront of prioritizing, designing, carrying out, and synthesizing research that helps Ontario and Canada fulfill legal international agreements. Important uncertainties in addressing these issues are lack of (1) soil carbon and hydrology data sets for adequate modelling and (2) understanding critical soil carbon and hydrological processes to improve modelling capabilities. Therefore, we use carbon cycling and hydrology as common linkages among the three research themes.

This five-year strategy is based on a synthesis of the results of a workshop titled *Integrating OMNR Research Priorities and Climate Change: Soil and Water Resources* held February 15 – 16, 2005 in Sault Ste. Marie, as well as new policy directions introduced since that workshop. Attendees at the workshop included representatives of academia, the Canadian Forest Service, the U.S. Forest Service, OMNR, and BIOCAP Foundation, who were divided into working groups to address: (1) forest management and soil carbon cycling and (2) the role of riparian zones, peatlands, and aquatic ecosystems in carbon cycling. The two groups identified management and research uncertainties and developed general strategies to address the uncertainties.

The FSWRP strategy consists of 10 sections, which are summarized briefly below:

1. **Program goals,** presents research goals for improving knowledge of the interactions between soil carbon and hydrological cycling and their integration into an indicator for sustainable forest management. This section also outlines short (<1 year), intermediate (1-3 years), and long-term (3-5 years) tactical goals for the program.

2. **Research hypothesis and conceptual framework**, outlines the general framework of the FSWRP as detailed below:

- ***Research hypothesis***. The central research hypothesis for the FSWRP is *that climate and geology are the major drivers of belowground carbon processes, with forest disturbance a secondary driver through its effects on hydrology and biogeochemistry.*

  Corollary 1: Carbon cycle and hydrological changes will significantly affect nutrient cycling and forest productivity, and may be positive or negative, depending on soil type, disturbance severity and frequency, and spatial and temporal variability.

  Corollary 2: Changes in forest soil carbon cycling and hydrology will modify the carbon balance in forests, which may have important consequences for global climate change.

  Corollary 3: Carbon cycling and hydrology can be used to indicate the ecological integrity of forest ecosystems within the Area of the Undertaking (AOU; i.e., Ontario's managed forest area).

- ***Conceptual framework.*** The elements of the FSWRP's research plan include: (1) long-term monitoring and surveys of natural variation of forest ecosystems in space and time, (2) experimental manipulation of forest structure, (3) synthesis of results through modelling at stand and landscape scales, and (4) feedback from the synthesis and modelling to identify gaps in knowledge and refine hypotheses.

3. **Policy directions**, discusses current and emerging policy drivers at provincial, national, and international levels and the FSWRP's approach to addressing the policy drivers, as well as the program's links to national research networks.

4. **2006-2011 research direction,** presents the uncertainties in carbon processes and water cycling. A major challenge in designing and applying research to develop, refine, and support sustainable forest management decision frameworks in the AOU is that 40% of the land base consists of interconnected forested, wetland, and freshwater (streams, lakes) ecotones. Thus, disturbances due to harvesting or fire can result in cascading effects on various carbon and hydrological processes within a forested landscape that may have negative implications for ecosystem health and forest productivity. Significant advances are needed to (i) identify and understand key soil carbon and hydrological processes to improve modelling capabilities and (ii) improve in-situ remote data acquisition systems for intensive monitoring of research sites, and provide greater spatial coverage of extensive sites to adequately understand and describe soil and water properties and processes at various spatial and temporal scales.

5. **Research program,** provides an overview of the research design and key deliverables of the riparian zone management, silviculutre and soils, and climate change research themes.

- ***Study design***. The FSWRP uses a suite of intensive study sites to identify and understand soil carbon and hydrological controls on forest and aquatic productivity. For the riparian management research, the intensive study site is maintained in partnership with the Canadian Forest Service-Great Lakes Forestry Centre (CFS-GLFC) near White River. For the silviculture and soils research, the intensive sites are located near Cochrane, Timmins, Foleyet, and Kapuskasing. The intensive site network is also used to parameterize and validate biogeochemical and hydrological models. A suite of extensive sites intensively studied by partners is used to test whether the soil carbon and hydrological responses to disturbance identified at the intensive sites hold across climatic and geological zones. This helps to reduce uncertainties in model results and increases confidence in applying research results to policy and management decisions.

- ***Research projects***. The FSWRP has three research themes: (i) riparian zone management, (ii) silviculture and soils, and (iii) climate change. The latter includes two project areas: (a) watershed carbon budgets and (b) peatland management. Key research deliverables, delivery mechanisms, and 2006-2011 research directions are described for each project.

  Riparian zone management

  - Understand the hydrological, carbon, nutrient, and vegetative interactions of riparian zones, their influence on adjacent aquatic ecosystems, and their response to forest disturbance.
  - Evaluate how riparian carbon and hydrological processes are associated with aquatic ecological patterns and processes.
  - Parameterize and validate applicable models that include hydrological and biogeochemical cycling to guide understanding and predictions of the role of riparian zones in forested landscapes.

  The research focus for 2006-2011 will be to quantify riparian zone alkalinity (e.g., acid buffering capacity) production, consumption, and fluxes in forested, alder, and fen riparian zones. Previous research identified that, of the three riparian types, riparian fen peatlands were the most important to stream buffering capacity. Therefore, this five-year period will be used to describe acidification and alkalinization rates in riparian fens under anoxic and oxic conditions in terms of how water table fluctuation frequencies affect (1) organic matter decomposition and peat acidification and alkalinization rates, (2) peat exchange processes for acidic cations with base cations and the longevity of these reactions before acidification of peat porewater and stream water occurs, and (3) calcite equilibrium reaction rates and the longevity of fen peat carbonate pools at the upper and intermediate peat depths.

  Silviculture and Soils

  - Understand soil carbon and nutrient cycles and their response to forest disturbance and regeneration.
  - Parameterize and validate applicable models that include carbon and nutrient cycling to improve understanding and guide predictions of nutrient availability and productivity throughout stand development.

  The silviculture and soils project direction for 2006-2011 will focus on two areas:

  - Modelling, in collaboration with Dr. Dave Morris, MNR-CNFER, and other partners (yet to be determined) to build a soil carbon and nutrient modelling strategy and research direction to understand forest succession, soil nutrient depletion, availability and uptake, and forest productivity.
  - Understanding water table controls on carbon cycling, specifically the role of fluctuating water tables on dissolved organic carbon cycling in forest soil.

  Climate change

  Watershed carbon balances

  - Understand the hydrological, biogeochemical, and vegetative effects on trace gas cycling and fluxes from soil and surface water and responses to forest disturbance.
  - Link carbon fluxes and storage in uplands, riparian zones, and surface waters to develop a carbon budget for boreal mixedwood watersheds.
  - Parameterize and validate applicable models that include trace gas cycling to guide understanding and ability to predict the role of riparian zones and aquatic systems in trace gas exchange. This will be synthesized to provide thresholds to support the use of criteria and indicators for state of the forest reporting.

The watershed carbon budget project direction for 2006-2011 will focus on three areas:

- Partitioning carbon fluxes in uplands, riparian zones, streams, and lakes and measuring carbon storage in stream and lake sediments.
- Developing a GIS database for the White River site to be used in association with geostatistics to produce interpolated maps to display digital versions of upland and riparian soil and vegetation carbon storage and CO_2 and CH_4 fluxes, and surface water sediment C storage and CO_2 and CH_4 fluxes.
- Modelling, that is integrating research results into a modelling framework using two models; (i) a geochemical model (PHREEQ) developed by the U.S. Geological Survey and (ii) a carbon and nitrogen model (Wetland-DNDC) developed by the U.S. Forest Service and the University of New Hampshire. The models are being used to predict trace gas fluxes and their biogeochemical and hydrological controls. Results will be incorporated into the carbon cycling and sensitive riparian wetland components of the riparian zone management strategy.

Peatland management

- Understand the interactions of vegetation and hydrology on carbon pools in peat, litter, and vegetation (both above- and belowground), carbon accumulation rates, and trace gas fluxes for diverse peatland types.
- Develop a statistically sound peatland inventory to support estimates of peatland contributions to Ontario's carbon balance.
- Evaluate how various peatland management strategies can be integrated on a landscape. This information will be synthesized to improve OMNR's ability to accurately conduct trace gas budgeting in response to the Kyoto Protocol.
- Develop, parameterize, and validate applicable models that include hydrological and biogeochemical cycling to guide the understanding and improve the ability to predict the role of peatlands in Ontario's carbon balance.

The peatland management project will focus on two areas:

- Reducing uncertainties in peatland carbon budget by using data from two Ontario Geologic Surveys to identify levels of uncertainties and their influences on peatland carbon storage component of the budget. These uncertainty values will be used to develop a statistically valid inventory to more accurately estimate the carbon budget of Ontario peatlands.
- Synthesizing the literature on peatland management and climate change. The synthesis will focus on peatlands and global warming and address:
  - Carbon functions of different peatland types
  - Forest management (i.e. pressure on forested peatlands from wood supply shortfalls)
  - Peat mining for energy
  - Peatland flooding for hydro-electric power
  - How (if?) these can be used in integrated resource management planning.

The synthesis will identify global warming potential for various peatlands and their sensitivities to management options for northern Ontario. Important uncertainties will be addressed, such as carbon pools and fluxes and conceptual and predictive model development. The information will be used to lay the foundation for a management strategy for northern Ontario peatlands in partnership with the OMNR's Lands and Water Branch.

Research program synthesis

The ultimate goal of the FSWRP is to integrate the individual projects through remote sensing and spatial modelling. Therefore, our partnership network is critical. It allows expertise from various disciplines to be obtained and retained and also brings together a number of research areas that can be used as intensive or extensive sites depending on the specific issue, which is important for the modelling component of the research. The partnership network also provides the ability to respond quickly when issues related to soil and water, identified by the Science and Information Resources (SIRD), Forest (FD), or Natural Resource

Management (NRMD) Divisions, require rapid turnover because the research site infrastructure is already in place. We will work with our research partners to incorporate riparian zone management, silviculture and soils, and climate change carbon and hydrological research into a spatial modelling strategy for northern Ontario's forested landscapes. This modelling strategy will be the focus for the subsequent five-year (2012-2017) FSWRP strategy.

6. **Partnerships**, presents FSWRP partnerships both internal and external to OMNR. External partnerships include academia, federal agencies, private companies, non-governmental organizations, and First Nations.

7. **Staffing**, discusses current and projected FSWRP internal and external staffing requirements.

8. **Program development**, discusses the role of the FSWRP in identifying emerging issues and the research undertaken to respond to specific issues.

9. **Technology transfer**, presents the FSWRP transfer approach.

10. **Program funding and challenges**, discusses the funding mechanisms used by the FSWRP and identifies major threats to achieving planned deliverables. These are (1) lack of flexibility within FRDS to proceed rapidly when emerging issues arise, (2) lack of long-term funding commitments, (3) human resource issues, including post-doctoral and graduate student access to OFRI's facilities, and (4) restrictions on out-of-province travel, which hinders the ability to present information to partners and to attend partnership meetings outside Ontario.

Program Goals

Forested landscapes in northern Ontario's boreal forest consist of low-lying, hydrologically connected upland, wetland, and aquatic ecosystems. The flow of water, carbon, and nutrients (e.g., hydrochemistry) through forested landscapes is critical to forest and aquatic productivity and thus, sustainability. Moreover, riparian zones are the key hydrochemical transfer points from uplands and wetlands to aquatic ecosystems. Soil chemical and physical properties, in large part, control the hydrochemical cycling and fluxes and as a result aquatic ecosystem health. Unfortunately, hydrochemical linkages among the different ecosystem components in northern Ontario are poorly understood.

Societal pressures, such as mill closures and high energy costs have placed growing demands on northern Ontario's forest resource. At the same time, changes in climate (e.g., temperature and precipitation patterns) are occurring in parts of northern Ontario. However, confidence in current ability to predict how northern Ontario's forests will respond to intensified management and changes in climate is low. Therefore, the Ontario Ministry of Natural Resources (OMNR) requires an enhanced understanding of boreal forest dynamics in three important areas: riparian zones, soil productivity, and climate change.

This strategy illustrates how the Forest Soil and Water Research Program (FSWRP) within the Forest Research and Development Section (FRDS) of the OMNR has incorporated riparian zone management, silviculture and soils, and climate change research into a comprehensive package that supports OMNR's need to design innovative management strategies within a continuously evolving arena of natural resource policy. Two highly uncertain soil processes are carbon and water cycling in forested ecosystems and their responses to disturbance and climate change. Thus, the central question guiding our research is: *How do forest harvesting, silvicultural interventions, natural disturbances, and climate change affect carbon and nutrient dynamics, water flow, and forest and aquatic productivity in Ontario's boreal forests?*

The FSWRP goals are to (1) improve OMNR's knowledge of the interactions between soil carbon and water cycling and (2) integrate soil carbon and water cycling into an indicator for sustainable forest management. This will be ccomplished by conducting research on (1) hydrochemical cycling and fluxes among upland forests, wetlands, riparian zones, and streams to develop appropriate forest management decisions for shoreline forests, (2) hydrological controls on soil carbon cycling for use in refining forest management strategies, and (3) temperature and precipitation controls on hydrochemical linkages among upland forests, riparian zones, wetlands, and aquatic ecosystems to improve understanding of hydrological connectedness among the various forest ecosystem compartments. This will support the development of indicators.

We have also set a series of short- (less than 1 year), intermediate- (1 to 3 years), and long-term (3 to 5 years) tactical goals, to ensure that the program's integrity and continuity are maintained as research, policy, and management drivers evolve within OMNR's Science and Information Resources Division (SIRD), Forest Division (FD), and Natural Resource Management Division (NRMD) and at international and national levels. In addition to the research program, the FSWRP retains time to address the immediate needs of its main client, OMNR's Forest Division. Table 1 outlines the FSWRP's short-, intermediate-, and long-term tactical goals.

Research Hypothesis and Conceptual Framework

Hydrological and carbon cycling and fluxes are important controls on aboveground forest (e.g., Gower et al. 1996, Cannell and Thornley 2003, Hamel et al. 2004) and aquatic (e.g., Fischer and Likens 1973, England and Rosemond 2004) structures and functions. For example, hydrology in part controls net primary production (NPP), constrains organic matter decomposition that recycles/makes available macro and micro nutrients and releases greenhouse gases (CO_2, CH_4, N_2O) and transports nutrients and C between ecosystems. Hydrology and carbon processes are in turn significantly influenced by climatic and geologic settings (e.g., Bouchard and Jolicoeur 2000, Horn 2003, Akselsson et al. 2004). Therefore, the central research hypothesis for the FSWRP is that *climate and geology are the major drivers of belowground carbon processes, with forest disturbance acting as a secondary driver through its effects on hydrology and biogeochemistry*.

Table 1. *Short-, intermediate, and long-term goals of the Forest Research and Development Section's (FRDS) Forest Soil and Water Research Program within this five-year strategy*

Term	Goal	Approach
Short (less than 1 year)	Expand rapport with Forest Management Branch (FMB)	• Define immediate research needs related to soil and water issues in consultation with FMB • Develop mechanism to deliver on immediate needs related to soil and water issues
	Refine communication strategy	• Improve communications with OMNR Regions and Districts • Encourage Regional staff to be directly involved with research projects
	Develop a marketing strategy for the Forest Soil and Water Research Program	• Work in collaboration with FRDS Management Team
	Improve recognition of FRDS and Forest Soil and Water Program	• Expand partnerships within OMNR
	Transfer programs and findings	• Attend Workshops • Present findings • Produce and distribute publications
Intermediate (1 to 3 years)	Acquire Personnel	• Solidify shared GIS/modelling position within FRDS
	Develop long-term vision for Geochemistry Laboratory	• Collaborate with Laboratory Group Leader and FRDS Management Team
	Transfer program and findings	• Present at Forest Joint Branch Leadership Team • Attend workshops • Produce peer-reviewed publications • Write white papers / literature syntheses
	Evolve partnership network	• Host graduate students/post docs • Host coop placements
	Develop inter-ministerial network	• Build relationships with Ministry of Energy and Ontario Ministry of Agriculture and Food
Long (3 to 5 years)	Build international research network	• Formulate partnerships with U.S. and European researchers
	Develop spatial model for research deliverables	• Integrate greenhouse gases, hydrochemistry, and nutrient cycling
	Adapt communications and marketing to meet changing needs for forest research/policy/management integration	• Work in collaboration with Forest Research and Development Section Management Team, Forest Management Branch, and Science and Information Branch
	Establish state-of-the-art biogeochemistry laboratory facilities	• Collaborate with Laboratory Group Leader and FRDS Management Team
	Build upon inter-ministerial network	• Solidify relationships with MOE and OMAF
	Solidify multi-year funding assurances through granting networks internal and external to the provincial government	• Identify funding opportunities and prepare and submit proposals
	Transfer program research	• Present at OMNR's Forest Division Joint Branch Leadership Team • Present at OMNR's Executive Committee • Attend workshops • Write peer-reviewed publications • Write white papers / literature syntheses
	Ensure relevancy of research	• Synthesize data and refine hypotheses

Corollary 1: Carbon cycle and hydrological changes will significantly affect nutrient cycling and forest productivity, and may be positive or negative, depending on soil type, disturbance severity and frequency, and spatial and temporal variability.

Corollary 2: Changes in forest carbon cycling and hydrology will modify the carbon balance in forests, which may have important consequences for global climate change.

Corollary 3: Forest soil carbon and hydrology can be used to indicate the ecological resilience of forest ecosystems within the Area of the Undertaking (AOU) (i.e., Ontario's managed forest area).

Figure 1 provides a conceptual model of the FSWRP research hypothesis. In this hypothesis, climate and geology drive physical, chemical, and biological properties. Those properties interact to regulate biogeochemical cycles of terrestrial and aquatic ecosystems, with riparian zones forming the critical link between upland and wetland ecosystems. These interactions have consequences for both forest and aquatic productivity. Atmospheric carbon dioxide (CO_2) can either interact with climate, biological, physical, and chemical factors including direct influence on aquatic productivity through effects on aquatic photosynthesis.

The elements of the FSWRP research plan include: (1) long-term monitoring and surveys of natural variation of forest ecosystems in space and time, (2) experimentally manipulating forest structure and ecosystem conditions followed by careful monitoring, (3) synthesizing results of (1) and (2) through modelling at stand and landscape scales, and (4) evaluating the synthesis and modelling results to identify gaps in knowledge and refine hypotheses. Over the long term, the FSWRP will take a holistic view towards forest ecosystem research to understand soil carbon and hydrological responses to natural and anthropogenic disturbances by addressing carbon and hydrological cycling and fluxes, and the contributions of uplands, riparian zones, and wetlands to aquatic acidification and watershed carbon balances. This is exceptionally important in addressing soil carbon and hydrologic responses to unprecedented human and natural disturbances including flood, drought, and fire, which are increasing in frequency.

Policy Directions

Policy drivers

Policy drivers and management approaches are rapidly evolving at international, national, and provincial levels. Activities that have occurred in recent years at all of these levels have important implications for forest management on Crown land in Ontario. For example, the OMNR has recently

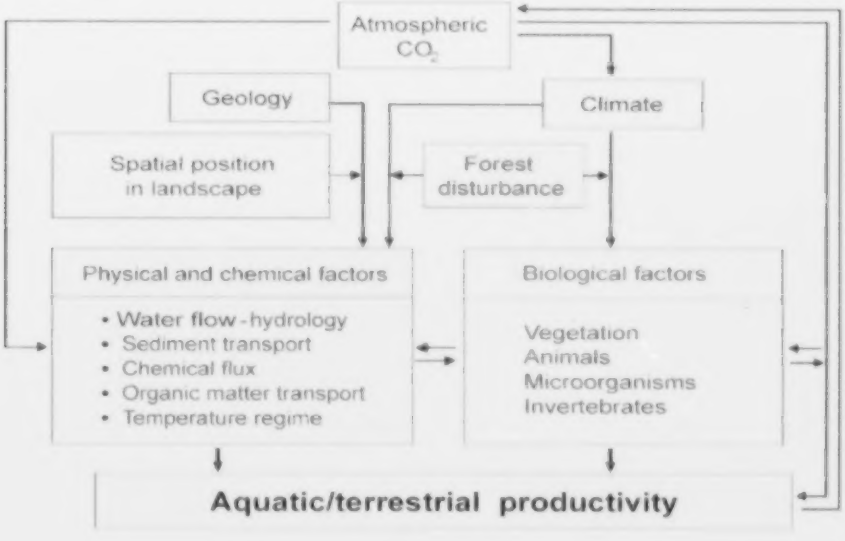

Figure 1. *Conceptual model of OMNR's Forest Soil and Water Research Program's overall research hypothesis. Grey boxes indicate research focus areas.*

published two documents: *Our Sustainable Future*, which establishes the framework for sustainable resource management in Ontario (OMNR 2005a) and *Science for Our Sustainable Future: A Science Strategy for the OMNR* (OMNR 2005b), which provides the framework that OMNR's science organizations will use to address the goals outlined in the former document. In addition and more directly related to soil and water issues, in March 2006 OMNR's Executive Committee directed that a framework be developed for a policy on the use of peat as a fuel source (Gleeson et al. 2006). Furthermore, international agreements, such as the Kyoto Protocol (United Nations Framework Convention on Climate Change: UNFCCC 1998) and the United Nations Economic Commission for Europe (UNECE) Convention on Long-Range Transboundary Air Pollution (LRTAP) (UNECE 2004) will also affect resource management decisions on Crown land.

Using forest biomass for fuel (e.g., Layzell et al. 2006; Walburger et al. 2006) is another rapidly emerging issue that may have implications for forest policy in Ontario. Initial discussions are focusing on using forest roadside slash piles and currently allocated wood in forest management plans not harvested due to lack of markets as fuel sources to help reduce energy costs for the forest sector in Ontario. Current OMNR guides (e.g., Protection of the Physical Environment; Archibald et al. 1997) are robust and will protect long-term site productivity under this scenario. However, examples in the literature suggest that biomass exports from Canada to Europe and Asia will increase to help offset their energy needs (e.g., Ericsson and Nilsson 2004, Parikka 2004, Hillring 2006). Thus, OMNR needs to be in position to make rapid, but scientifically sound integrated land management policy decisions in response to evolving policy drivers at various jurisdictional levels.

Forest Soil and Water Research Program approach to addressing policy drivers

The FSWRP is adapting to address these new policy directions and has developed this research strategy for 2006-2011. The strategy will help the FSWRP to remain at the forefront of soil and water research needs in this increasingly complex forest policy paradigm. This five-year strategy is based on a synthesis of research needs and priorities identified at a workshop titled *Integrating OMNR Research Priorities and Climate Change: Soil and Water Resources* held February 15 – 16, 2005 in Sault Ste. Marie (details in Appendix I), as well as policy directions that have been released since then. Workshop participants included representatives of academia, Canadian Forest Service, U.S. Forest Service, OMNR, and BIOCAP Foundation. Following the session two working groups were established, one to address forest management and soil carbon cycling and the other to deal with the role of riparian zones, peatlands, and aquatic ecosystems in carbon cycling. Both working groups identified management and research uncertainties for their respective topics and developed general strategies to address those (listed in Appendix II).

The FSWRP's research is linked to emerging OMNR research priorities as well as existing OMNR strategies and legal documents as follows:

- ***Our Sustainable Future:*** by reducing uncertainties in the effects of disturbance on forest and peatland soil, groundwater, and surface water resources to support the vision of *a healthy environment that is naturally diverse and supports a high quality of life for people of Ontario through sustainable development*.
- ***Science Support for Enhancing Forest Productivity and Mitigating Wood Supply Shortfalls:*** by understanding (1) carbon and hydrological cycles of forested catchments to improve management decisions using shoreline forests to offset wood supply shortfalls and (2) nutrient cycling, depletion, and uptake in regenerating forests to improve management decisions using silvicultural options to mitigate wood supply shortfalls.
- ***Ontario Forest Accord:*** by understanding the role of riparian zones in mitigating the environmental impacts of silvicultural operations on aquatic resources.
- ***Ontario's Living Legacy Land Use Strategy:*** by addressing the role of disturbance in water cycles in headwater catchments.
- ***Climate Change and MNR: A Strategy and Action Plan:*** by reducing the uncertainties associated with (1) forest management and climate change on water, carbon, and nutrient cycling, (2) the contribution of peatlands to Ontario's carbon budget, and (3) developing the climate change science priorities to both support and guide peatland management policy development for northern Ontario.

The FSWRP is also linked to the Forest Class Environmental Assessment (EA) Condition EA 29(a) through defining acceptable assessment methodologies and EA 29(b) through defining the timing of monitoring activities (OMNR 2003). As well, three elements have been added to OMNR's 2006 State of the Forest Report's Global Ecological Cycles Criterion; (1) *Monitoring Forest Production of Nitrous Oxide* (4.3.1), (2) *Monitoring Acid Rain Deposition* (4.3.2), and (3) *Monitoring Evapotranspiration* (4.4.1). The FSWRP contributed significantly to their development in partnership with OMNR's Forest Management Branch (FMB). The program will provide supporting information for reporting on each of the elements. OMNR is also currently developing a new stand-level forest management guide that will consider hydrological responses of forest disturbance and their effects on aquatic ecosystems. These will require research support since presently the ability to predict aquatic ecosystem or long-term soil recovery responses to forest disturbance is limited.

Program links to national research networks

The FSWRP is also directly linked to national research networks and programs, such as the National Aquatic Systems and Climate Change Research Network (NASCC-RN), Fluxnet-Canada (e.g., Canadian Carbon Program) Research Network, the Sustainable Forest Management Network (SFMN), and BIOCAP Foundation. This allows program staff to remain on the forefront of prioritizing, designing, carrying out, and synthesizing research that helps Ontario and Canada to fulfill national and international agreements, such as the Kyoto Protocol and the UNECE-LRTAP. The latter addresses Canada's legal obligation to establish and report on critical loads of aquatic acidity and when those are exceeded. These international agreements will likely affect forest management decisions and policy development within the OMNR. For example, in the 2004 Acid Rain Report for Canada (Environment Canada 2004) it was estimated that 45 million hectares of Ontario forests currently exceed the critical load for aquatic acidity or are near threshold levels. Important uncertainties related to addressing these issues are lack of soil and hydrological databases for adequate modelling and limited understanding of soil carbon and hydrological cycles to improve modelling capabilities.

2006-2011 Research Direction

Understanding watershed carbon processes in the boreal zone of Ontario is essential because this region is important to the global carbon balance. The boreal zone contains 90 to 290 Gt (1 Gt = 1 Pg = 10^{15} g) of carbon in upland forest soils and 220 to 490 Gt of carbon in peatland soils (Schlesinger 1977, Gorham 1991, McGuire et al. 1995, Goodale et al. 2002, Houghton 2003), which accounts for 66% of the global terrestrial soil carbon pool and 59% of the total (soil plus plant biomass) global carbon pool (Kasischke et al. 1995; McGuire et al. 1995). Ontario accounts for approximately 10% of both the global total boreal peatland (McLaughlin 2004) and forested upland (Liu et al. 2002) soil carbon, and about three-fourths of the Ontario soil carbon pool occurs in peatlands.

Forest productivity and responses to disturbance are controlled by the interaction between hydrology and carbon cycling, which is important for (i) establishing bounds on wildfires and controlling frequency and intensity of fires (Stocks et al. 1998, Hely et al. 2001), (ii) regulating nutrient cycling and fluxes (Morris et al. 1997, Hobbie et al. 2000, McLaughlin et al. 2000, McLaughlin and Phillips 2006), (iii) regulating greenhouse gas (e.g., CO_2, CH_4, N_2O) cycling and fluxes to the atmosphere from terrestrial and aquatic ecosystems (Rudd et al. 1974, Schiff et al. 1998, Algesten et al. 2003, Bastviken et al. 2004), (iv) regulating forest succession (Arseneault 2001, Bergeron et al. 2001), and (v) regulating forest (Hamel et al. 2004) and aquatic (Wallace et al. 1999) productivity. Understanding the interactions between hydrology and carbon cycling will therefore improve our capacity to predict forest management interventions on forest and aquatic productivity and how they are influenced by changes in temperature and precipitation.

Up to 40% of the land base in the boreal region of Ontario consists of hydrologically interconnected forested, wetland, and freshwater (streams, lakes) ecotones, with riparian zones being a critical carbon and water transfer point (Molot and Dillon 1996, McLaughlin 2004, McLaughlin et al. in review). Unfortunately the understanding of these interconnected systems is poor. Disturbances such as forest harvesting or fire can result in cascading effects on various hydrochemical processes within a forested landscape that may jeopardize ecosystem health and forest productivity (Buttle et al. 2000, Price and

Waddington 2000, Price et al. 2005). Consequently, devising sustainable management schemes within Ontario's Forest Class EA's AOU requires a more thorough understanding of soil carbon and hydrological cycles.

Research partnerships within OMNR, and with the federal government, academia, private sector, non-governmental organizations (NGOs), and First Nation groups are providing data sets required to develop upper and lower bounds on soil carbon stocks and losses and variability in hydrology (i.e., water table heights, water flow paths, stream flow rates) to improve understanding of, and ability to predict, the interactions between forest management and climate change on forest and aquatic productivity. This will contribute to higher certainty when making forest policy decisions.

Spatial modelling is required to describe and predict disturbance effects on forest soil carbon and hydrology and place those into a sustainable forest management context (Band et al. 1996, Yarie 2000, Zhou et al. 2004). Successful spatial modelling requires integrated knowledge of both carbon processing and hydrological connections among forests, riparian zones, wetlands, and surface water (Buttle et al. 2000, 2004; Trettin et al. 2001). Furthermore, increased emphasis on landscape management (e.g., OMNR 2001) requires improvements in soil and hydrological mapping tools to acquire comprehensive spatial data sets. These data sets will facilitate the development, parameterization, and validation of the models needed to address current and emerging soil and water issues related to sustainable forest management. The understanding of carbon cycling in forest, aquatic, and peatland ecosystems and how it responds to various disturbances also is very rudimentary (e.g., Moore et al. 1998, Hobbie et al. 2000, Billett et al. 2006). These uncertainties need to be reduced and efforts need to focus on parameterizing and validating process-based models and then coupling them to spatial models for scaling from the site- to landscape-level (Trettin et al. 2001, Landsberg 2003, Cui et al. 2005). Minimizing these uncertainties are just a few of the research priorities that the FSWRP hopes to address over the next few years as outlined below.

Research Program

Study design

The FSWRP uses a suite of intensive study sites to identify carbon cycling and hydrology in different interconnected patterned ecosystem types (i.e., forest, riparian, wetland, and aquatic systems) and their controls on forest and aquatic productivity. For the riparian zone management research, the main study site is located near White River, Ontario (Figure 2) (McLaughlin et al. in review), and is maintained in partnership with the Canadian Forest Service-Great Lakes Forestry Centre (CFS-GLFC). The focal sites for the silviculture and soils research include Cochrane (Stand-Level Adaptive Management (or SLAM) study; MacDonald et al. 2003), Timmins/Foleyet (Natural, Extensive, Basic, Intensive, and Elite Silvicultural Intensity (or NEBIE) study (Bell et al. 2006) and Fluxnet-Canada (Margolis and Coursolle 2003)), and Kapuskasing (NEBIE) (Figure 2). The collective intensive site network is used to understand carbon and hydrological cycles and test biogeochemical and hydrological models. A suite of extensive sites managed by program partners (who use them for their research) is used to test whether the biogeochemical and hydrological responses to disturbance identified at the

Figure 2. *Location of study sites for OMNR's Forest Soil and Water Research Program within the Timber Class Environmental Assessment's Area of the Undertaking in Ontario.*

intensive sites holds across climatic and geological zones. This helps to reduce uncertainties in model results and increases our confidence in applying findings to forest policy and management decisions.

The research section of the strategy is divided into three major themes: riparian zone management, silviculture and soils, and climate change. The latter focuses on watershed carbon budgets and the role of peatlands in Ontario's carbon budget. The ultimate goal is to integrate the three research areas through remote sensing and spatial modelling (Figure 3). Therefore, our partnership network is critical to the program. It allows expertise from various disciplines to be obtained and retained and brings together a number of research sites that can be used intensively or extensively depending on the specific issue, which is important for the modelling component of the research. The partnership network also provides the ability to respond quickly when soil and water issues arise from OMNR's Science and Information Resources Division (SIRD), Forest Division (FD), or Natural Resource Management Division (NRMD) because the research site infrastructure is already in place.

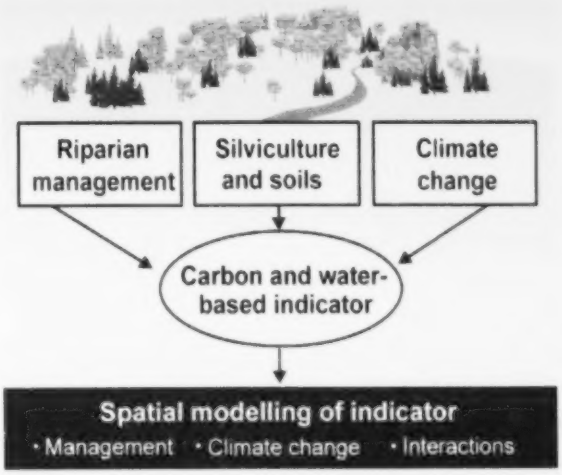

Figure 3. *Conceptual framework to integrate riparian management, silviculture and soils, and climate change research for spatial modelling of carbon- and water-based indicators of forest sustainability.*

Research projects

Riparian zone management

Key research deliverables

Riparian zones are transitional areas between terrestrial and aquatic environments that influence landscape-level processes by regulating the flow of energy, nutrients, sediments, and water between terrestrial and aquatic ecosystems (Naiman and Decamps 1997; Naiman et al. 2005). However, data on the hydro-biogeochemistry of riparian zones are insufficient to guide and support riparian policy directions (Hornbeck and Kochenderfer 2000; Buttle et al. 2004; Merrill and Benning 2006).

The ultimate goal and deliverable of the riparian zone management project is to improve knowledge of hydrological interactions with (1) carbon dynamics and greenhouse gas exchange and (2) soil decomposition concomitant with nutrient mineralization in riparian zones to develop appropriate forest management decisions for shoreline forests associated with streams. The objective is to understand the key hydro-biogeochemical connections of diverse riparian zones to more effectively integrate uplands, riparian zones, and aquatic ecosystems in a riparian zone management strategy.

The field design, field sampling, and laboratory analyses used for the study are outlined in McLaughlin et al. (in review).

The project provides scientifically sound information to:

- Understand the hydrological, carbon, nutrient, and vegetative interactions of riparian zones, their influence on adjacent aquatic ecosystems, and their response to forest disturbance.
- Evaluate how riparian carbon and hydrological processes are associated with aquatic ecological patterns and processes.
- Parameterize and validate applicable models that include hydrological and biogeochemical cycling to guide understanding and predictions of the role of riparian zones in forested landscapes.

Results are incorporated into OMNR's five year state of the forest reports, specifically the criteria for the *Conservation of Soil and Water Resources* and *Global Ecological Cycles* as well as providing scientific support for the development of the stand-level forest management guide. The riparian project also addresses the role of climate change and carbon and hydrological fluxes from riparian zones to streams, as discussed in more detail in the *Climate Change* section of this strategy. Future goals are to integrate

the effects of forest harvesting, natural disturbances, and climate change into an assessment of stream health to provide an indicator of forest sustainability.

Background information

A major issue that Ontario's forest sector is struggling with is wood supply shortfalls (e.g., Bell et al. 2000). Conducting more intensive harvesting and silvicultural operations within riparian areas are management strategies receiving increasing consideration to help offset those shortfalls (e.g., Berg 1995, Verry and Dolloff 2000, Beach and Halpern 2001). However, data on the hydro-biogeochemistry of riparian zones are insufficient to guide and support riparian policy directions (Hornbeck and Kochenderfer 2000, Buttle et al. 2004, Merrill and Benning 2006).

In addition to regional concerns such as wood supply shortfalls, global issues that include climate change (e.g., Kyoto Protocol), acidic deposition, and critical load exceedances of acidity for forest soils and aquatic ecosystems (e.g., UNECE-LRTAP) need to be incorporated into riparian management planning in the AOU. For example, aquatic acidity critical loads are currently exceeded for 10% to 20% of lakes in eastern Canada, with another 9% of lakes near their critical load exceedance threshold (Henriksen et al. 2002, Dupont et al. 2005). It has also been suggested that forest harvesting will lead to higher percentages of lakes exceeding acidity and/or nearing the critical load exceedance thresholds; in fact, approximately 45 million hectares of forested land in Ontario is exceeding or near the threshold of forest soil acidity critical loads (Environment Canada 2004). Because many lakes in the boreal zone of Ontario are connected by stream networks, it is essential to understand stream hydrochemical inputs into lakes and hydro-biogeochemical controls within upland forests and riparian zones. Moreover, preserving riparian zones might prevent aquatic systems from reaching this critical load, and may be a reason to retain non-harvested riparian zones.

With the adoption of landscape management planning that emulates natural disturbances (e.g., OMNR 2001, Macdonald et al. 2004, Nitschke 2005) it is also essential that riparian functions be more thoroughly understood and assessed across spatial and temporal scales (e.g., Naiman and DeCamps 1997, Verry and Dolloff 2000, Naiman et al. 2005). This is a difficult task because the complexity of riparian zones is high, even in the same geologic setting. For example, in the same boreal headwater catchment, riparian zones can vary in structure and width from (i) narrow strips in confined reaches dominated by deciduous or coniferous trees to (ii) wide floodplain forests dominated by coniferous trees, (iii) floodplain swamps dominated by nitrogen (N)-fixing vegetation, and (iv) bog and fen peatlands. Each riparian type will have unique hydro-biogeochemical functions and will respond differently to natural and anthropogenic disturbances (e.g., Tabacchi et al. 1998, Merrill and Benning 2006). However, most studies and modelling efforts have been reported for watersheds that are rather simple in terms of stand structure and lack extensive riparian areas (e.g., Aherne et al. 2004, 2006). Thus, understanding of watersheds with multiple riparian types is limited and results are difficult to apply in more complex watersheds of the AOU.

Riparian research direction

Forest, alder, and fen peatland riparian types are common along streams in the boreal zone (Timoney et al. 1997, Arseneault 2001, Busse and Gunkel 2001, Harper and Macdonald 2001, Hylander et al. 2002, Jacks and Norrstrom 2004). Moreover, understanding the controls on alkalinity (e.g., acid buffering capacity) production and fluxes in upland and riparian soils are important to addressing forest soil and aquatic acidity critical loads exceedances. Our research therefore addresses hydrological controls on riparian zone carbon cycling and alkalinity production, consumption, and fluxes in forested, alder, and fen peatland riparian types (McLaughlin et al. in review). Soil solution, groundwater, and surface water alkalinity are largely the result of dissolved inorganic carbon (DIC) and subsequent carbonate equilibrium reactions. Dissolved inorganic carbon is composed of various carbonate compounds [i.e., free-CO_2, carbonic acid (H_2CO_3), bicarbonate (HCO_3^-), or carbonate anion (CO_3^{2-})] depending on solution pH (Szaran 1998). Three principle sources of DIC are: (1) organic matter decomposition (Anderson et al. 1986, Compton 1988, Ogrinc et al. 2003, Turetesky and Ripley 2005), (2) carbonate- and silicate-based mineral weathering (Johnson et al. 1968, Telmer and Veizer 1999, Szramek and Walter 2004), and (3) atmospheric CO_2 influx (Palmer et al. 2001, Finlay 2003), all of which are subject to pH-induced carbonate chemistry equilibrium reactions.

Free-CO_2 and H_2CO_3 dominate at pH values below 4.0, free-CO_2 / H_2CO_3 and HCO_3^- are the principal DIC forms between pH 4.0 and 8.0, with HCO_3^- increasing at higher pH values; and CO_3^{2-} contributes mostly to DIC at pH values greater than 10 (Szaran 1998). Organic anions (e.g., carboxyl groups; COOH), however, can be important to alkalinity in soil and surface water with pH values below 5.0 (Hemond 1980, McKnight et al. 1985, Siegel et al. 2006). In contrast, phenol (Φ-OH) groups contribute to alkalinity above pH 10. Water in most boreal streams and lakes falls between pH 4.0 and 8.0, thus is composed mostly of CO_2 / H_2CO_3, HCO_3^-, and organic acid carboxyl groups, with the latter two contributing to alkalinity (Neal 2001).

Results from 2002-2005 indicate that of the three riparian types studied (i.e., fen, forested, alder), riparian fens are the most important to stream alkalinity and base cation flux (McLaughlin et al. in review). This interpretation is based on:

- Higher amounts of exchangeable bases in fen peat and their fluxes compared to the alder and forested riparian zones (exchangeable calcium (Ca) and magnesium (Mg) were 15 to 95 times higher in the fen than the alder and forested riparian zones, while exchangeable silicate (Si) was at least five times higher in the fen).
- Carbonates accounted for 8% of the total peat carbon between 0 and 40 cm below the surface and 80% between 80 and 100 cm below the peat surface.
- Soil solution calcium ion (Ca^{2+}) concentrations were 3.0 and 3.7 times higher in the fen than the forested or alder riparian zones, respectively, and HCO_3^- concentrations 12.0 and 3.3 times higher in the fen soil solution than the forested or alder riparian types.
- Base cation and HCO_3^- fluxes from the riparian fen were similar to total watershed fluxes, while fluxes from the forested and alder riparian types were at least 50% lower than total watershed fluxes.
- The water table position in riparian fen peatlands accounted for 92% of the explained variability in stream flow and 71% of explained variability in total watershed HCO_3^- alkalinity concentrations and flux and a threshold water table elevation of 10 cm below the peat surface was necessary before significant stream flow generation occurred in response to rainfall events, even when the alder soils were near saturation.
- Similarity in the $\delta^{13}C$-DIC values between the fen deep groundwater and stream indicate potentially similar DIC sources for stream and fen groundwater.

McLaughlin et al. (in review) provide a more in-depth discussion of the methodologies and results. They developed a conceptual model for alkalinity production for the fen riparian type (Figure 4A, 4B), where lowering of the water table leads to an increase in the thickness of the riparian-fen acrotelm (aerobic portion of peat) and organic matter decomposition shifts from anoxic to oxic reactions in the acrotelm of the peat. The more rapid decomposition increases acidity production and decreases peat solution HCO_3^- alkalinity, with the acidic cations [hydrogen (H^+) and ferric iron (Fe^{3+})] exchanging for Ca^{2+} and Mg^{2+} on peat exchange sites, increasing peat porewater pH over the short-term, but acidifying the fen peat. In contrast, when water table levels are high, soil bacterial syntrophic [organic matter hydrolyzing, iron (Fe) reducing, sulphur (S) reducing, and methane producing (methanogenic bacteria)] relationships consume acidity and produce alkalinity (Conrad 1996, Schink 1997). At least 98% of the anaerobic carbon flow occurs through hydrolyzing bacteria in peatlands rather than Fe and S reducers or methanogens at high water table levels (e.g., Vile et al. 2003). The latter three terminal carbon reactions, however, metabolize H^+ and organic acids, which prevents the inhibition of organic matter hydrolyzing bacteria (Phelps and Young 1997, Schink et al. 2000, Muller 2003, Carmona and Diaz 2005).

More rapid carbon dioxide (CO_2) efflux from the peat to the atmosphere occurs under low water table levels and decreases its residence time in the peat thereby stimulating HCO_3^- production. The rapid CO_2 efflux also promotes calcite precipitation, further reducing HCO_3^- and acidifying the peat. In addition, Fe and S oxidation rates increase, producing sulphate (SO_4^{2-}) and supplying acidity to the peat. Base cations exchange with the Fe^{3+} and H^+, with SO_4^{2-} and dissolved organic carbon (DOC) being the major counter ions for the released base cations. Sulphate and DOC fluxes during and after large rainfall events following droughts of even two months in duration can exceed fluxes during the entire snow-free period under 'normal' precipitation years; however, HCO_3^- fluxes are significantly lower. The snow-free period hydrologic base cation flux from the fen does not initially differ, but the counter ions do, with HCO_3^- important under high water table and SO_4^{2-} and DOC important under low water table conditions. Equally important is a net acidification of the peat at low water table heights. Should

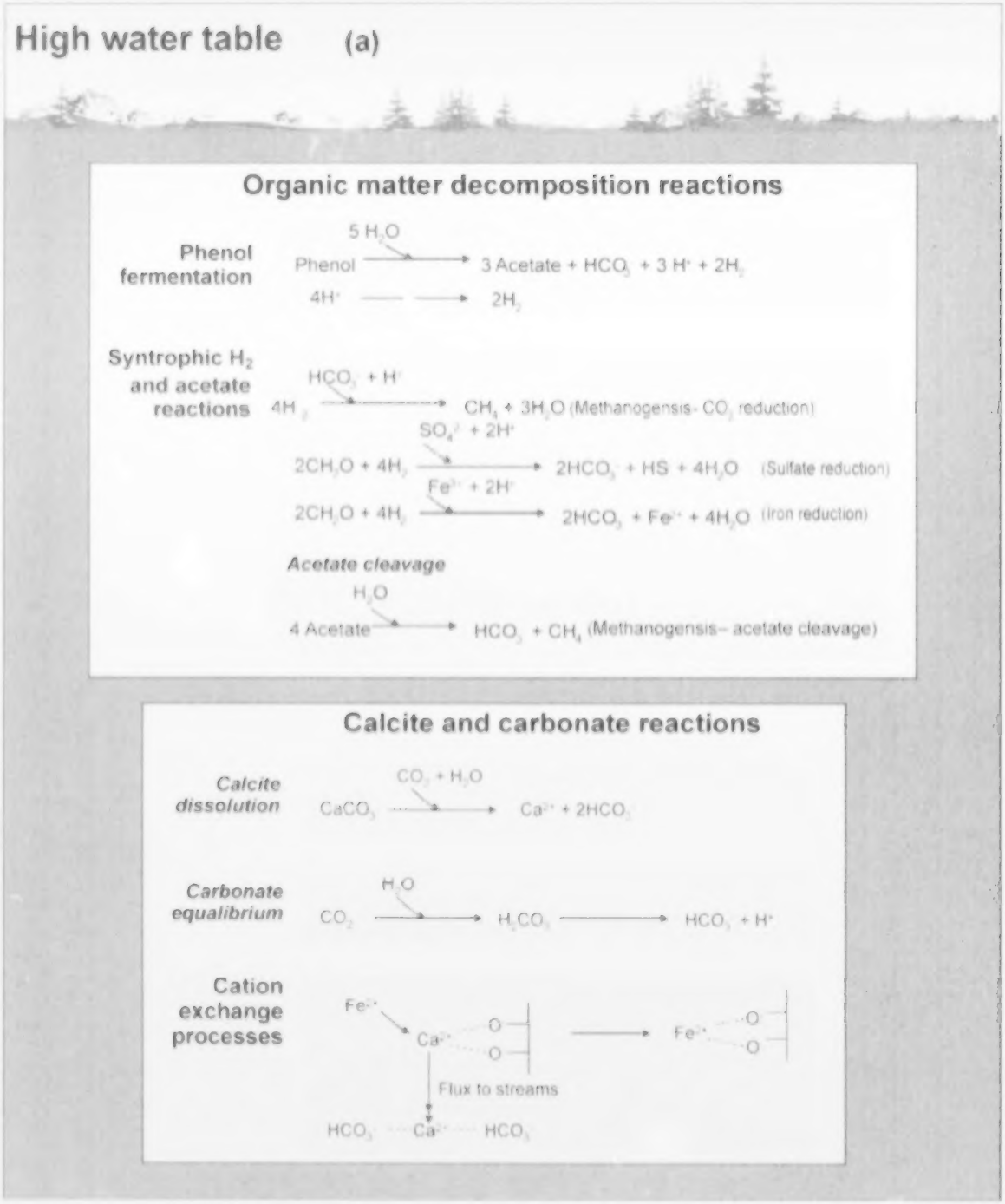

Figure 4. *Conceptual model of organic matter decomposition and alkalinisation and acidification of fen peatlands. (A) High water table organic matter, calcite equilibrium, and carbonate equilibrium reactions and (B) low water table organic matter, calcite equilibrium, and carbonate equilibrium reactions (from McLaughlin et al. 2007)*

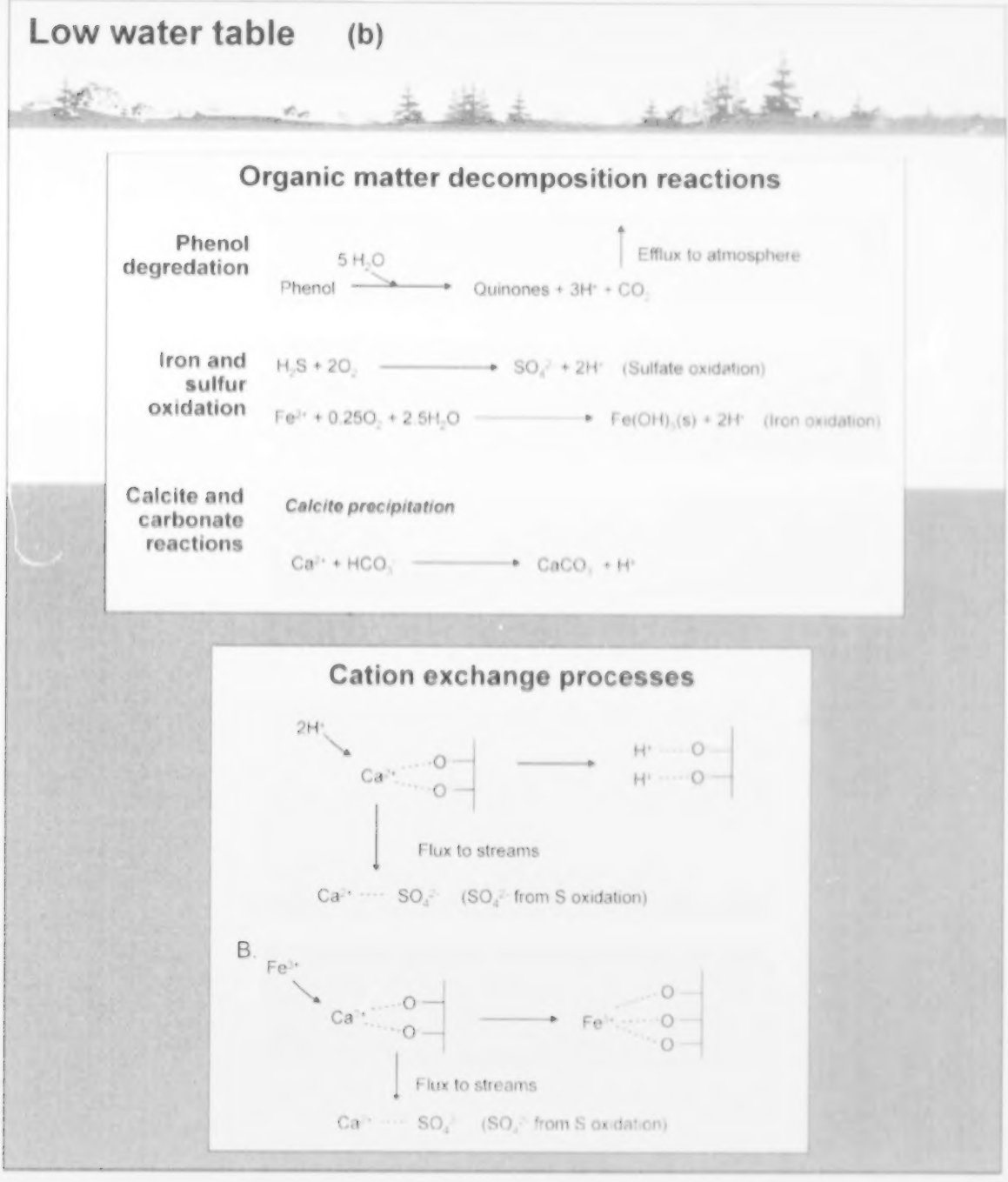

Figure 4. Continued

droughts become more frequent in summer, base cation depletion and H^+ enrichment of fen peat may occur. The H^+ would become important to charge-balancing SO_4^{2-} and DOC, resulting in subsequent stream acidification in the long term. Riparian fen peat acidification is a natural process, but data on acidification rates in those riparian types or responses to water table changes are limited.

Based on our conceptual model, a significant amount of research is required to adequately describe acidification and alkalinization rates in riparian fens under anoxic and oxic conditions in terms of how water table fluctuation frequencies affect (1) organic matter decomposition and peat acidification and alkalinization rates, (2) peat exchange processes for ferric and ferrous (Fe^{+3}) iron and H^+ with base cations and the longevity of these reactions before acidification of peat porewater and stream water occurs, and (3) calcite equilibrium reaction rates and the longevity of fen peat carbonate pools at the upper and intermediate peat depths. As well, a more in-depth understanding of the role of riparian fen flow reversals in providing Ca^{+2} and HCO_3^- to the surface peat and their fates is needed. Alkalinity research is being conducted in partnership with Drs. Sherry Schiff of the University of Waterloo, Martin Jurgensen of Michigan Technological University, and Nathan Basiliko of the University of Toronto at Mississauga.

The riparian zone management research focus over this five-year strategy is to (1) further improve understanding of the controls of alkalinity production and fluxes and (2) model organic matter decomposition, calcite and carbonate equilibrium, peat cation exchange, and alkalinity production and fluxes to streams in response to riparian fen peatland water table levels at the White River site. We will also provide data on the reaction rates for those processes to help constrain their variability for stream acidification modelling. The results will be integrated into a modelling framework using two models: (i) a geochemical model (PHREEQ) developed by the U.S. Geological Survey (Parkhurst and Appelo 1999) and (ii) a carbon and nitrogen model (Wetland-DNDC) developed by the U.S. Forest Service and the University of New Hampshire (Zhang et al. 2002). These models will be used to build predictions of DIC fluxes and stream buffering capacity and the role of forested upland and riparian harvesting, silvicultural interventions, and regeneration; the potential for coupling the models will also be examined. If the latter proves successful, integrating models of critical load exceedance and spatial models for watershed-based carbon fluxes and acidification will be explored.

Silviculture and soils

Key research deliverables

The ultimate goal and deliverable of the silviculture and soils project is to improve knowledge of soil carbon and hydrologic interactions for use in refining forest management strategies. This is accomplished by understanding the hydrological interactions with (1) carbon dynamics and greenhouse gas exchange and (2) soil decomposition concomitant with nutrient mineralization and their controls in regenerating and mature forests. The project provides scientifically sound information to:

- Understand soil carbon and nutrient cycles and their responses to forest disturbance and regeneration.
- Parameterize and validate applicable models that include carbon and nutrient cycling to improve understanding and guide predictions of nutrient availability and productivity throughout stand development.

Background information

Forest carbon management is a key component of sustainable forest productivity. Moreover, estimating carbon sequestration in Ontario is a challenge because not enough is known about how hydrology regulates carbon cycling (Trettin et al. 1995, 2001). Improved knowledge is also needed of carbon flows through various forest ecosystem pools, processes regulating those flows, and interactions between carbon flows and nutrient cycling. This will improve our ability to predict how forest management interacts with soil type dynamics to potentially affect forest productivity and help offset increases in atmospheric CO_2 concentrations. It is also important to understand how forest management can be implemented across landscapes to maintain balances between increased CO_2 sequestration and forest productivity. These types of data are also important inputs to forest carbon models, such as the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS) (Apps et al. 1999) or TRIPLEX (Peng et al. 2002). Results from this study are intended to support the rigorous defensible assessments of carbon cycles required under international agreements.

Boreal forests have an integral and increasingly important role in the global carbon budget (Gorham 1991, O'Neill et al. 2003). Total global soil carbon pools are estimated at between 1150 to 1500 Gt (1 Gt = 10^9 tons = 10^{15} g) (Goodale et al. 2002, Houghton 2003, Grace 2004) with about one-third to one-half of that in boreal forests. In the boreal zone, on average, 60-70% of the carbon is stored in dead organic matter (soils, detritus, and other debris) and about 30-40% in aboveground biomass (Hobbie et al. 2000, Bhatti et al. 2002). The high proportion of soil carbon is due to short growing seasons, cool temperatures (both of which restrict production), slow decomposition rates and nutrient turnover, and carbon sorption to soil anion exchange sites (i.e., iron- and aluminum-oxides) (Gorham 1991, McLaughlin et al. 1994, Hobbie et al. 2000, 2002, Prescott et al. 2000, Bhatti et al. 2002). Since much of the Forest Class EA's AOU covers the boreal zone, Ontario is in a position to be a leader in managing forests for increased carbon sequestration in response to international drivers.

The role of hydrological processes in balancing boreal forest harvesting, natural disturbance, regeneration, and carbon sequestration has not yet been investigated or integrated into an assessment of forest sustainability in Ontario or elsewhere in North America. However, data are available for each individual component (e.g., Nalder and Wein 1999, Harden et al. 2000, Bhatti et al. 2002, O'Neill et al. 2002, 2003, Wilson et al. 2002, Wirth et al. 2002, McLaughlin and Phillips 2006). The research challenge is to incorporate hydrology, forest harvesting and regeneration, natural disturbances, and carbon sequestration into a concise program that can aid in developing optimum management strategies to support the management of boreal landscapes. Research projects such as NEBIE, SLAM, and Fluxnet-Canada, as well as others (e.g., McLaughlin et al. 2000, Duckert and Morris 2001, Morris et al. 2005, McLaughlin and Phillips 2006) are pivotal to developing the whole-ecosystem carbon science for boreal forest management. Understanding how soil carbon can be managed to maintain or enhance forest productivity and carbon sequestration requires improved insight into forest soil carbon and hydrologic responses to different disturbances and efforts to reduce uncertainties in model projections.

Silviculture and soil research direction

Modelling: Early research suggested that initial carbon and nutrient depletion along with compaction and rutting following full-tree harvesting were major threats to forest sustainability (Weetman and Webber 1972, Malkonen 1974, Kimmins 1977, Covington 1981). However, recent literature from long-term study sites across North America indicates that forests are very resilient in terms of soil carbon, nutrients, and physical site disturbance (McLaughlin et al. 1996b, Trettin et al. 1997, Johnson and Curtis 2001, Yanai et al. 2003, Morris et al. 2005, Powers et al. 2005, McLaughlin and Phillips 2006). Moreover, following initial reductions in soil carbon and nutrients after harvest, recovery has been relatively quick (e.g., within 10 to 20 years) (Olsson et al. 1996, McLaughlin et al. 1996b, Powers et al. 2005, McLaughlin and Phillips 2006). Nonetheless, long-term effects of forest harvesting on soil nutrients are not well documented in the literature, especially for northern boreal forests (Pussinen et al. 2002, Hunt et al. 2003, Peltoniemi et al. 2004). For instance, the relationship among post-harvest succession and nutrient availability, depletion, and uptake are not well documented. This is important because at crown closure regenerating forests have the highest demands for soil nutrients (Switzer and Nelson 1972, Cole 1995, Frelich and Reich 1995). As stand development continues, tree demand for nutrients decreases and leaching rates may increase (Cole 1995; McLaughlin et al. 1996a, b; McLaughlin and Phillips 2006). The balance of nutrient pools between these two successional stages may affect nutrient depletion responses in subsequent rotations.

Integrating the effects of climate change on nutrient cycling and stand regeneration also is not well documented in the scientific literature. For example, changes in climate can benefit or limit regeneration and productivity, depending largely on soil conditions (Gower et al. 1996, Dale et al. 2001, Bouchon and Arseneault 2004). Thus, a more complete understanding of the interactions among climate change, forest regeneration, and productivity is needed to refine management strategies.

The project's modelling efforts will be accomplished in collaboration with Dr. Dave Morris of OMNR's Centre for Northern Forest Ecosystem Research (CNFER). Other partnerships will be pursued to build a soil carbon and nutrient modelling strategy and research direction to understand interactions among forest succession, soil nutrient depletion, availability and uptake, and forest productivity. We will also

collaborate with researchers in Michigan and Maine and initiate discussion with staff of the U.S. Forest Service in Minnesota to access data and/or partake in research at the Marcell Experimental Forest long-term study on harvesting and soil nutrients in northern Minnesota. These partnerships will provide access to data from a suite of long-term sites in eastern North America to support soil carbon and nutrient cycling and forest regeneration scenario modelling.

Water table controls on carbon cycling: Modelling of carbon cycling and budgets in Ontario is hampered by poor understanding of the effects of water table fluctuations on soil carbon because most research and models were developed for well-drained forest soils (e.g., Trettin et al. 2001, Zhang et al. 2002). This is important because fluctuating water tables affect about 40% of the forested land in the AOU. We hypothesize that due to these fluctuations, DOC is an important control on soil nutrient cycling and the carbon balance of Ontario forests. But, DOC cycling has yet to be incorporated in forest ecosystem carbon budget models.

Although simulations indicate that DOC affects forest carbon sequestration rates and soil CO_2 production, our understanding of these processes is very rudimentary. For instance, few studies have considered the role of DOC in mineral soil carbon storage in temperate and boreal forests and they report highly variable DOC contributions (i.e., ranging from 25 to 90%) (Neff and Asner 2001, Michalzik et al. 2003). Incorporating soil DOC cycles in carbon models could result in a forest being a net carbon sink, whereas, based on aboveground vegetation or only including contributions of roots to soil carbon, the same models indicate the forest is a net carbon source (Neff and Asner 2001). In addition, up to 30% of microbial activity can occur below 40 cm depth (with DOC a significant organic matter supplier), contributing to nutrient cycling and CO_2 fluxes from soils during fall and winter when few studies document these processes (Goulden et al. 1998, Hobbie et al. 2000). Unfortunately, these concepts are neither well understood nor accounted for in most forest carbon models.

Most uncertainty in DOC cycling and fluxes centres on (1) rates of production and consumption by soil microorganisms (Moore et al. 1998, Guggenberger and Kaiser 2003, Tipping et al. 2005) and (2) sorption and desorption rates to, and from, mineral soil exchange sites (McLaughlin et al. 1994, Neff and Asner 2001, Kalbitz et al. 2003, Michalzik et al. 2003). Up to 60% of the variability in mineral soil organic carbon storage simulations have been attributed to mineral soil DOC sorption and desorption rates (McLaughlin et al. 1994, Fiedler and Kalbitz 2003). Moreover, less complex DOC is produced through anaerobic reactions when the water table is at, or near, the soil surface (McLaughlin et al. 1996b, in review). These anaerobic reactions can lead to (1) larger fluxes of high-energy DOC to aquatic systems and (2) more available carbon for soil microbial consumption, increasing nutrient cycling rates when the water table decreases. Thus, understanding how fluctuating water tables control DOC cycling and refining knowledge of DOC cycling would improve productivity modelling efforts.

The water table fluctuation and DOC research of the FSWRP is being conducted in a boreal mixedwood forest at the Ontario flux station near Foleyet, Ontario, which is part of the Fluxnet-Canada research network, in partnership with Drs. Tim Moore of McGill University and Changhui Peng of the University of Quebec at Montreal. Two models are being tested for their potential to predict DOC cycling and its contribution to mineral soil carbon storage under fluctuating water tables: (1) Wetland-DNDC and (2) DyDOC, developed by the Centre for Hydrology and Ecology in the United Kingdom (Michalzik et al. 2003). One of these models will be selected and parameterized using data from the Ontario Fluxnet site. Once parameterized, the model will be used to predict the contribution of DOC to mineral soil carbon sequestration at the Ontario flux station. By coupling the model with TRIPLEX (in partnership with Drs. Peng and Moore), we anticipate that use can be expanded to other Fluxnet-Canada and forested research sites in Ontario that have different disturbance regimes and forest successional stages. This will lead to improved spatial and temporal modelling of forest carbon balances.

Synthesis: Forest carbon management is a key component of sustainable forest productivity and understanding its response to, and recovery from, disturbances is critical to sustainable management of Ontario's boreal forest. However, both understanding of, and ability to predict soil carbon cycling in Ontario forests is poor. Important needs include improvements in (1) soil data sets to support modelling long-term forest productivity and carbon

balances and (2) understanding of DOC contributions to carbon accumulation and nutrient cycling.

Dissolved organic carbon has been identified as an important, but poorly understood, component of soil nutrient cycling and subsequent forest productivity and carbon balances. The proposed DOC research and modelling work will significantly improve spatial and temporal modelling of aspects of soil productivity to better refine management strategies that consider (1) the Kyoto Protocol, (2) critical load exceedances for aquatic acidity to fulfill Canada's commitment to the UNECE-LRTAP, and (3) changes in forest succession and productivity to improve Ontario's stand-level forest management guide.

Climate change

Watershed carbon budget

Key research deliverables

The ultimate goal and deliverable of the watershed carbon budget project is to improve knowledge of the controls of trace gas [CO_2 and methane (CH_4)] fluxes from watersheds and the role of upland forest, riparian zone, peatlands, and aquatic ecosystems in Ontario's carbon balance. We do this by examining the key roles of diverse riparian zones and streams and lakes on trace gas exchange and watershed carbon accumulation rates in a boreal mixedwood watershed. The project provides scientifically sound information to:

- Understand the hydrological, biogeochemical, and vegetative effects on trace gas cycling and fluxes from soil and surface water and their responses to forest disturbance.
- Link carbon fluxes and storage in uplands, riparian zones, and surface waters to develop a carbon budget for boreal mixedwood watersheds.
- Develop, parameterize, and validate applicable models that include trace gas cycling to guide understanding and predictions of the role of riparian zones and aquatic systems in trace gas exchange. This will be synthesized to provide thresholds to support the use of criteria and indicators for state of the forest reporting.

Background information

Climate change, clean water, clean energy, and wood supply shortfalls are among the greatest challenges OMNR will face in the 21st Century. Moreover, the International Panel on Climate Change (IPCC) has recently provided a framework for trace gas budgeting and reporting for wetlands and aquatic ecosystems (IPCC 2003). However, Ontario currently lacks the ability to conduct the rigorous carbon budget accounting required under aquatic and wetland IPCC guidelines. Given the extent of Ontario's peatland, riparian, and freshwater ecosystems (approximately 40% of the total land area) (Molot and Dillon 1996, McLaughlin 2004), advancing understanding of the factors regulating greenhouse gas sources and sinks in those three ecosystems could be important components of a long-term Ontario strategy to mitigate climate change. Trace gas cycling and fluxes within forests, peatlands, and aquatic systems and their interactions are thus critical research needs (e.g., Tremblay et al. 2005).

Uncertainties inhibiting the development of trace gas budgets are a lack of data related to carbon cycling and water flow through forest catchments. Reducing hydrological uncertainties is thus critical to partitioning carbon transport at landscape control points such as riparian zones. Because riparian zones are linked to streams and lakes via surface and subsurface flows, they transport dissolved carbon to surface waters (McGlynn and McDonnell 2003, Worrall et al. 2005, McLaughlin and Phillips 2006). Carbon cycling processes in surface waters are therefore closely linked to their neighbouring terrestrial ecosystems. For example, the organic carbon content of lakes and streams in the boreal zone is a function of the amount of riparian peatlands (Eckhardt and Moore 1990, Elder et al. 2000, Hope et al. 2001, Huttunen et al. 2002, Algesten et al. 2003). The amount of carbon moving through riparian zones can range from 20 to 40% of total soil respiration comprising a significant component of the carbon balance (Kling et al. 1991, Clair et al. 1999). This hydrological efflux and subsequent CO_2 losses from aquatic systems is generally on the same order of magnitude as soil C sequestration rates (Hope et al. 2001, Welsch and Hornberger 2004). Thus, some research indicates that changes in aquatic CO_2 efflux can alter the carbon balance of a watershed (Billett et al. 2004, Worrall et al. 2005, McLaughlin and Phillips 2006).

The high organic carbon content in boreal lakes and streams draining catchments with high proportions of riparian peatlands causes water to be supersaturated with CO_2 and CH_4 (and possibly N_2O) relative to the atmosphere, and a net release of gaseous carbon occurs (Kling et al. 1991, Huttunen et al.

2002, Jonsson et al. 2003). Thus, streams and lakes function as conduits for carbon exchange between terrestrial ecosystems and the atmosphere. Integrating trace gas and hydrologic carbon fluxes from streams and lakes with terrestrially-based CO_2 net ecosystem exchange (NEE) measurements may influence whether a watershed is interpreted as a net carbon sink or source (Billett et al. 2004, 2006; Dawson et al. 2004). However, to complete the carbon budget of forested watersheds, measurements are also required of stream and lake sediment carbon content and trace gas flux at the lake/atmosphere interface (Molot and Dillon 1996, Dillon and Molot 1997, Hanson et al. 2004). For instance, boreal lake sediments are estimated to contain 17% of a boreal landscape's total carbon (Molot and Dillon 1996) and emit between 20 and 30% of the carbon to the atmosphere (Algesten et al. 2003). Understanding these processes is important to understanding the fundamentals of boreal greenhouse gas budgets.

A true assessment of the carbon balance of forest ecosystems in Ontario, therefore, requires that losses and gains of carbon in drainage waters, surface waters, riparian zones, and peatlands be included in terrestrial carbon budgets (Molot and Dillon 1996, Hanson et al. 2004, McLaughlin 2004). Furthermore, because aquatic carbon fluxes and soil sequestration rates are comparable, aquatic carbon fluxes may offset future changes in soil carbon storage (Einsele et al. 2001).

Watershed carbon budget research direction

A preliminary carbon budget has been completed for one of the watersheds at the White River site (Figure 5A, 5B). At this site, riparian peatland carbon storage was more than three times that estimated for the upland forest, riparian forest, and riparian alder sites on a unit-area basis (Figure 5A, McLaughlin et al. in review). As part of this study, the area of each ecosystem type within the watershed will be used to scale the data to the watershed level. McLaughlin et al. (in review) also reported that fen peatlands are an important hydrological linkage providing dissolved carbon to draining streams. Others have also found that the percentage of the watershed occurring as fen riparian areas is an important control on hydrological DOC, DIC, and CH_4 flux, where watersheds with large fen riparian areas have high hydrological carbon fluxes (Eckhardt and Moore 1990, Halsey et al. 1997, Aikenhead et al. 1999).

The upland forest was a net sink of about 23 g C m^{-2} (Figure 5A). Riparian zones were either net carbon sinks, sources, or neutral depending on type (Figure 5A) and climatic conditions; for example, McLaughlin et al. (in review) found that riparian poor-fens are net sinks, whereas rich-fens and riparian forests were carbon neutral, and alder stands were a net carbon source. The stream and lake (into which the stream drains) were also net sources. The hydrological carbon flux was dominated by DOC, although DIC contributed

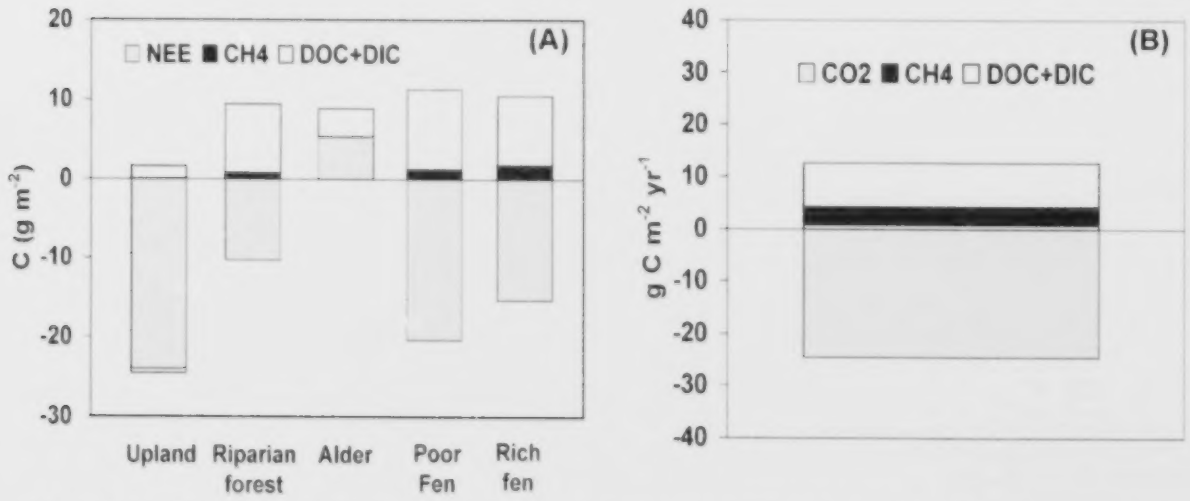

Figure 5. Carbon balance for a (A) the upland forest and different riparian zones and (B) total watershed for a boreal mixedwood watershed in northeastern Ontario.

30 to 40% of the flux. Overall, the watershed was a sink of 11.2 g C m^{-2} (Figure 5B). For trends, multiple years of data scaled to the watershed-level based on the area of each ecosystem component are needed, which will be a FSWRP focus over the next five years. The role of climate on the watershed carbon budget needs to be better defined. Therefore, the FSWRP will also continue to partition trace gases between soil and atmosphere and hydrologic fluxes from riparian zones, measure trace gas emissions from streams and lakes, and carbon burial in stream and lake sediments.

Results will be incorporated into a GIS database and integrated into a modelling framework using PHREEQ and Wetland-DNDC in conjunction with the riparian zone management project. The models are being used to build predictions of trace gas fluxes and their biogeochemical and hydrological controls; potential for coupling these models will be examined in 2007-08. If that proves successful, then integrating the spatial models for watershed-based carbon and nitrogen fluxes will be explored in future years.

Once parameterized and validated, these models will support improved understanding of terrestrial and aquatic carbon balances. Modelling efforts will help to illustrate the controls on trace gas fluxes. Coupling this with analyses and syntheses of the post-harvest samples will provide a more in-depth understanding of forest harvesting on watershed carbon budgets that will provide important data to measuring Ontario's forest carbon balance. The results will then be incorporated into the carbon cycling and sensitive riparian wetland components of riparian zone management research. To accomplish this, the FSWRP will form research partnerships within the National Aquatic Systems and Climate Change Research Network and with Drs. Carl Trettin and Randy Kolka of the U.S. Forest Service.

Peatland management

Key deliverables

The ultimate goals and deliverables of the peatland management project are to (1) improve knowledge of the role of peatlands in ecosystem dynamics and carbon budgets and (2) provide science support for a peatland management strategy for northern Ontario. We also hope to better understand the key roles of diverse peatlands in climate change. The project provides scientifically sound information to:

- Understand the interactions of vegetation and hydrology on carbon pools in peat, litter, and vegetation (both above- and belowground), carbon accumulation rates, and trace gas fluxes for diverse peatland types.
- Develop a statistically sound peatland inventory to support estimates of peatland contributions to Ontario's carbon balance.
- Evaluate how various peatland management strategies can be integrated on a landscape. (This information will be synthesized to improve OMNR's ability to accurately conduct trace gas budgeting in response to the Kyoto Protocol.)
- Develop, parameterize, and validate applicable models that include hydrological and biogeochemical cycling to guide understandir.g and improve predictions of the role of peatlands in Ontario's carbon balance.

Background information

Wetlands cover only about 3% of the Earth's surface, but they are estimated to store about one-third (455 Gt of carbon) of the terrestrial soil carbon pool and represent 60% of carbon now stored in the atmosphere (Aselmann and Crutzen 1989, Gorham 1991). Northern wetlands have commonly been reported to sequester carbon at rates estimated between 5 and 85 g of carbon m^{-2} yr^{-1} or a total sequestration rate of 76 Tg of carbon (1 Tg = 1 million tons = 10^{12} g) annually for long-term storage as peat (Gorham 1991, Vardy et al. 2000, Gorham et al. 2003, Lavoie et al. 2005). Thus, northern wetlands may be significant in terms of the so-called 'missing sink' of global carbon (Houghton et al. 1998) and because they sequester large amounts of carbon, interest in the carbon balance of boreal peatlands and their role in global carbon cycles is tremendous.

Northern peatland ecosystems are the result of multiple sensitive interactions between hydrology and vegetation and thus they are responsive to changes in climate, drainage, peat harvesting, flooding, and forest harvesting (Trettin et al. 1995, 2006, McLaughlin et al. 1996b, 2000, Roulet 2000, Waddington et al. 2002, Laiho et al. 2003, Trettin and Jurgensen 2003, Zetterberg et al. 2004, Gleeson et al. 2006). Such disturbances could significantly affect local and regional hydrology, floral assemblages, ecosystem productivity, and carbon flux, affecting the carbon sink capacity of northern peatlands (Halsey et al. 1998). The carbon budget in peatlands is the product of (1) atmospheric uptake of CO_2,

(2) the delivery of organic carbon to the peat by vegetation as root exudates and fresh litter, (3) the transformation of organic and inorganic carbon by various aerobic and anaerobic microorganisms, and (4) hydrologically-driven mass flux of both organic and inorganic carbon through a system.

Canada has the second largest area of peatlands (1.24×10^{12} km^2) in the Northern Hemisphere, containing 154 Gt of carbon and accounting for approximately one-third of the carbon in all northern peatlands (Tarnocai 1998). Canadian peatlands also store about 60% more carbon than do equivalent areas of forest (Forestry Canada 1992). Ontario contains approximately 30% of the peatland area and carbon storage in Canada, thus Ontario peatlands likely play an important role in Canadian and global carbon budgets (McLaughlin 2004). Therefore, peatland management decisions made by OMNR may have national and global implications.

Peatland management in Ontario is a hotly debated emerging issue. Societal pressures such as alternative energy, northern Ontario economic stability, wood supply shortfalls, and mill closures and subsequent increased harvesting of conifer peatlands (e.g., spruce swamps) are important issues that require a science-based peatland management strategy (McLaughlin 2004, Gleeson et al. 2006). However, the effects of peatland disturbances in Ontario are not well documented. Therefore, the FSWRP has identified peatland management as an issue of immediate importance. The OMNR needs to define how, or if, peatlands can fit into integrated resource management planning by understanding the cumulative greenhouse gas dynamics, hydrology, and water quality implications of peatland management. Accomplishing this requires first identifying critical unknowns in carbon pools and fluxes, developing conceptual and predictive models, and initiating a provincial peatland carbon inventory that includes not only types of peatlands and their area, but also disturbance patterns and the interaction between hydrology and long-term carbon accumulation rates. This information then needs to be synthesized into a management strategy for northern Ontario peatlands.

Peatland research direction

Ontario peatland carbon budget: The Ontario Geologic Surveys for northeastern (Riley 1994) and northwestern (Riley and Michaud 1987) Ontario were used as initial data sets to estimate the area of different peatland types in the province (McLaughlin 2004). Data from those surveys and the published literature were used to develop carbon budgets for these peatlands (Table 2). Total peatland carbon storage in Ontario was estimated as 47.1 Gt of carbon, while long-term carbon accumulation rates were estimated between 29 and 36 g C m^{-2} yr^{-1}. Ontario peatlands represent 30% of carbon stored in Canadian peatlands and about 10% of carbon stored in northern peatlands worldwide. Conifer peatlands contain most of the carbon at 28.11 Gt.

The forest soil (non-wetland) carbon pool in Ontario was estimated as 10.95 Gt (Liu et al. 2002); combining the forest soil carbon pool with our calculated value of 47.1 Gt for peatlands, together peatlands and forest soils store 58.1 Gt of carbon in Ontario, with approximately 80% of that in peatlands. Conifer peatlands account for approximately 70% of the forest soil carbon in Ontario. Because forest carbon budget models commonly used in Canada and Ontario [e.g., Carbon Budget Model for the Canadian Forest Sector CBM-CFS (Apps et al. 1999), FORCARB (Plantinga and Birdsey 1993, Colombo et al. 2005), and TRIPLEX (Peng et al. 2002)] do not consider forested peatlands, a significant amount of the forest soil carbon in Ontario (and Canada) is not accounted for in carbon budgets. This limits adequate estimates of forest management, fire, or climate change effects on Ontario's forest carbon budget.

Calculations indicate that Ontario peatlands are a sink of 8.4 Tg (e.g., Mt) of carbon yr^{-1} (McLaughlin and Jurgensen, in review) (Table 2). Bogs, conifer peatlands, and thicket (e.g., alder) swamps all showed a net CO_2 uptake from the atmosphere, but fens emitted CO_2. Carbon losses through CH_4 flux were the lowest of the carbon parameters estimated (Table 2). The hydrological carbon flux represented the largest carbon loss in all peatland types, with DOC dominating the flux and with a range between 9 and 20 times greater than CH_4 losses from the peat surface to the atmosphere. In fen peatlands, DOC export was about 50% of the net CO_2 efflux (Table 3). Including DIC, the hydrological flux of carbon was nearly twice that of CO_2 efflux in fens, indicating the importance of hydrological carbon losses in the carbon balance. Based only on NEE calculations, bogs and thicket swamps would be considered net carbon sinks. However, including DOC and DIC fluxes in the equation makes those two peatland types emerge as net carbon sources.

Table 2. Carbon balance for major peatland types in Ontario (negative numbers indicate carbon uptake) (McLaughlin and Jurgensen, in review)

Flux component (Tg Cyr^{-1})	Peatland type				
	Bogs	Fens	Conifer	Thicket swamp	Total
CO_2	-0.64	0.23	-72.6	-0.39	-13.4
CH_4	0.1	0.05	0.27	0.06	0.48
DIC*	0.22	0.10	0.57	0.13	1.02
DOC*	0.73	0.35	1.93	0.45	3.46
Total	0.41	0.73	-9.83	0.25	-8.44

* DIC – dissolved inorganic carbon; DOC – dissolved organic carbon

Reducing uncertainties in peatland carbon budget: We are using data from the two Ontario Geologic Surveys to develop levels of uncertainties and their controls for the peatland carbon storage component of the carbon budget. For example, initial calculations indicate that for the total peat carbon pool, estimated values are ± 150%. This was not unexpected given that the Ontario Geologic Surveys were not designed for carbon balance and climate change studies. We are using these uncertainty values to estimate an adequate sample size for a statistically valid inventory to more accurately estimate the carbon storage in Ontario peatlands.

Literature synthesis on peatland management and climate change: A literature synthesis related to peatland management in Ontario is under development and will be completed in 2007-2008. It focuses on peatlands and climate change, and addresses:

- What's known about carbon fluxes and balances in different peatland types
- Effects of forest management resulting from pressure on forested peatlands to offset wood supply shortfalls
- Effects of mining peat for energy
- Effects of flooding peatlands for hydro-electric power development
- Possible uses for peatlands in integrated resource management planning

The information will be used to lay the foundation for a management strategy for northern Ontario peatlands to be developed in partnership with OMNR's Lands and Water Branch.

Synthesis: The major finding to date related to watershed carbon budgets is that uncertainty about the carbon balance is high and needs to be refined. Major uncertainties involve quantifying peatland trace gas, DOC, and DIC fluxes and carbon storage and long-term accumulation rates. These uncertainties require immediate refinements to accurately define the role of peatlands in Ontario's carbon budget. Ontario requires a statistically sound peatland inventory to support estimates of peatland carbon budgets and to determine the controls on carbon fluxes so they can be modelled and predicted.

Research program synthesis

Our riparian zone management research will focus on water table level controls on riparian fen peatland acid/base reactions by identifying water table changes affect on organic matter decomposition, calcite and carbonate equilibrium, and peat cation exchange processes. The research will support the development of a modelling strategy that will use process-based models to predict alkalinity production and consumption rates and its flux from riparian fens to streams.

The silviculture and soils research will focus on modelling forest carbon and nutrients over successional trajectories and identifying the role of fluctuating water tables on DOC cycling and its role in carbon sequestration, nutrient cycling, and forest productivity. This work will be incorporated into a spatial modelling framework using the TRIPLEX model to predict forest succession and changes in forest carbon in Ontario's forests.

Our climate change research will focus on two areas. First, we will further refine watershed carbon budgets and incorporate those into our riparian zone management modelling framework. Second, we will develop climate change, hydrological, and water quality research priorities for a peatland management strategy for northern Ontario focusing on peat extraction for energy, forested peatland harvesting, and hydroelectric power generation. The management strategy will also include the development of a peatland carbon inventory and describe the approach Ontario should consider for carbon accounting in wetlands under the IPCC guidelines.

The ultimate goal is to integrate the individual projects through remote sensing and spatial modelling (Figure 3). Therefore, our partnership network is critical. It allows expertise from various disciplines to be obtained and retained and also brings together a number of research areas that can be used as intensive or extensive sites depending on the specific issue, which is important for the modelling component of the research. The partnership network also provides the ability to move quickly when issues related to soil and water identified by OMNR's Forest or Natural Resource Management Divisions require rapid turnover because the research site infrastructure is already in place.

We will work with our research partners to incorporate riparian zone management, silviculture and soils, and climate change carbon and hydrological research into a spatial modelling strategy for Ontario's forested landscapes. This modelling strategy will be the focus of the next five-year (2012-2017) strategy for the FSWRP.

Partnerships

The FSWRP has been very aggressive in seeking partnerships with government, academic, private sector, non-governmental organizations (NGOs), and First Nation groups to address priority research areas and to integrate these with requirements set out in international and national agreements. The research partnership network is broad, multi-institutional, includes multiple Divisions and Branches within OMNR, and universities, private companies, and federal organizations across Canada and within the United States (Table 3). The overall partnership framework is shown in Figure 6. The partnerships serve to:

- Increase the profile of the FSWRP, FRDS, and OMNR at the local, regional, provincial, national, and bi-national levels.
- Provide professional training to college, university, and industrial employees and students to expand the trained workforce for natural resources management in northern Ontario.
- Ensure that the FSWRP, FRDS, and OMNR are leaders in soil and water research within applied research organizations, as well as remaining leaders in resource management.
- Seek research funds, with partner organizations

Table 3. *Organizations that partner with the Forest Soil and Water Research Program*

Business	Organization
Government	OMNR-Centre for Northern Forest Ecosystem Research
	OMNR-Northeast Science and Information Section
	OMNR-Northwest Science and Information Section
	OMNR-Ontario Terrestrial Assessment Program
	OMNR-Lands and Waters Branch
	OMNR-Ontario Parks
	Canadian Forest Service
	United States Department of Agriculture - Forest Service
Universities and colleges	Sault College
	College Boreal
	Trent University
	University of Guelph
	McGill University
	University of Waterloo
	Queens University
	University of Western Ontario
	University of British Colombia
	University of Quebec at Montreal
	Michigan Technological University
	McMaster University
	University of Toronto
Private sector	Digital WebWorks
	Domtar
	Tembec
	Bowater
	Weyerhaeuser
	Buchanan
	Mead-Westvaco
	PDK Projects, Inc
	Whelan Associates
Non-governmental organizations	National Council for Air and Stream Improvement
	Upper Lakes Environmental Research Network
	Manitoba Wildlands
First Nations Group	Poplar River First Nation

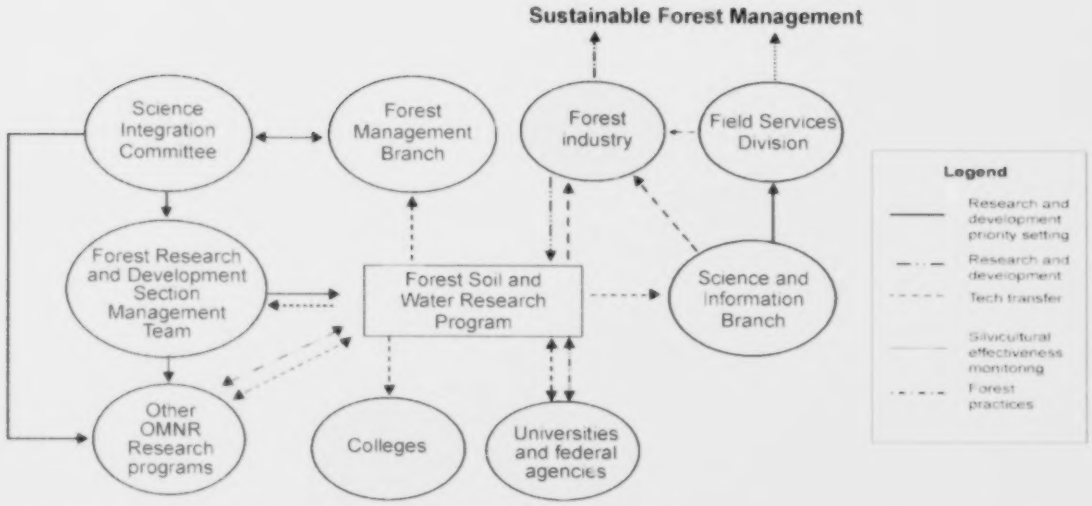

Figure 6. *Conceptual framework for the research and development partnership network for OMNR's Forest Soil and Water Research Program. Shaded circles are external organizations; remainder are OMNR divisions, branches, or sections.*

assuming a lead role, depending on the funding agency and scope of the proposed project.

- Develop and maintain working relationships with academia, government, private industry, non-governmental organizations (NGOs), and First Nations.

University partnerships

The FSWRP's partnerships with universities include those in Ontario, across Canada, and in the United States (Table 3), with adjunct faculty appointments at specific universities. The main intent of these partnerships is to:

- Aid university faculty in obtaining funds for projects that address OMNR priorities for soil and water research by being a co-principal investigator and contributing in-kind support and/or leveraging funds. The most common proposal submissions occur through:
  - National Centre of Excellence-Sustainable Forest Management Network (SFMN)
  - Natural Sciences and Engineering Research Council of Canada (NSERC)
  - Canadian Foundation for Climate and Atmospheric Sciences (CFCAS)
  - BIOCAP Foundation
  - U.S. National Science Foundation (NSF)
  - U.S. Department of Agriculture (USDA)
- Conduct research and development activities through graduate students and post-doctoral fellows that are beyond the expertise and capacity of OMNR staff, but critical to the FSWRP to achieve research deliverables. A schematic of the framework of FSWRP partnerships with universities is provided in Figure 7A.

College partnerships

The FSWRP has a Memorandum of Understanding with Sault College in Sault Ste. Marie and College Boreal in Sudbury, with anticipation of expansion to include other colleges.

Partnerships with colleges focus on assisting them with:

- Developing a trained workforce to support natural resource management in northern Ontario
- Improving college research capacity by joint acquisition of equipment
- Developing colleges as leaders in local economies by expanding their funding base

Workforce training is conducted in partnership with the FRDS Geochemistry Laboratory. A sequence of interactions with college students occurs, beginning with providing partial supervision of student research projects related to the FSWRP. If a student successfully completes their research

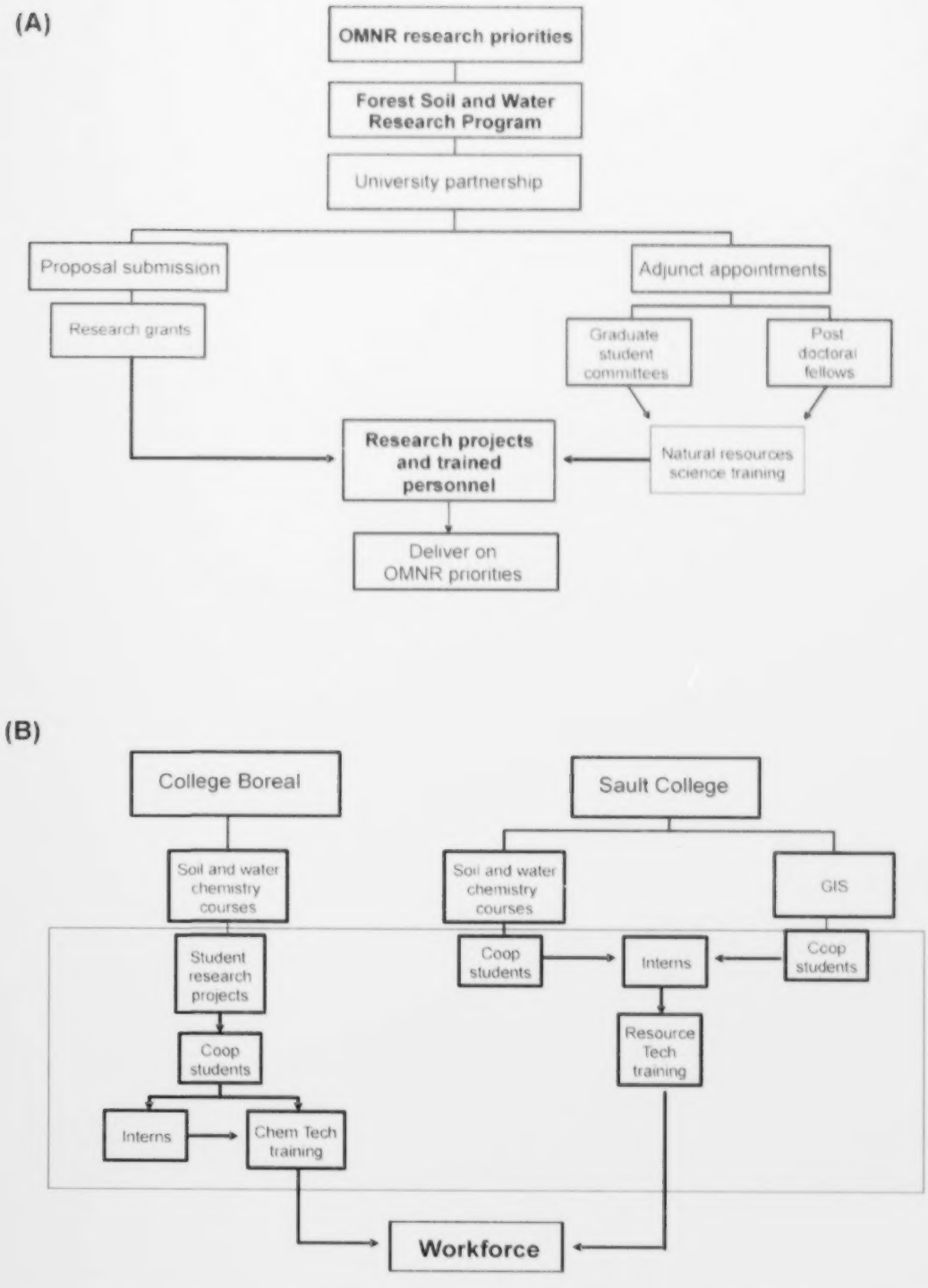

Figure 7. *Conceptual framework for OMNR's Forest Soil and Water Research Program university (A) and college (B) partnerships. Grey boxes indicate FSWRP training opportunities.*

project and indicates that s/he is seriously considering a career in natural resources then they are hired as interns through either the Natural Resources Canada Internship program or through OMNR's Internship program. If, following the internship the individual continues to be interested in a career in natural resources, s/he is hired as either an OMNR Chemical Technologist 1 or Resource Technician 1, depending upon the student's specific interest in natural resources and funding availability. An example of our partnership with northern Ontario colleges for workforce training is presented in Figure 7B, which illustrates the ideal sequence of events.

Another component of the technology transfer within college partnerships includes the transfer of research information from the program scientist and coordinator to college faculty as well as from college faculty to program staff. For example, program staff are working collaboratively with the Geographical Information System (GIS) program at Sault College to develop GIS and remote sensing databases for forest cover and soil and water components that will support spatial modelling of forest disturbance, hydrochemistry, nutrient cycling, and surface water quality and quantity. The information is transferred to students by Sault College faculty as part of their courses and to OMNR staff by FSWRP staff.

In cooperation with OMNR's geochemistry laboratory, the program is also beginning to assist the colleges in identifying funding opportunities within the federal and provincial governments and private industry to enhance their research capacity. As well, program staff are assisting colleges in obtaining federal and provincial grants so that they can remain leaders in the northern Ontario economy. These funding opportunities will further increase opportunities to maintain a highly trained workforce in natural resources within northern Ontario.

Non-governmental organization and First Nation partnerships

The FSWRP is partnered with various NGOs including the Upper Lakes Environmental Network (ULERN), the National Council for Air and Stream Improvement (NCASI), and Manitoba Wildlands. The program has also developed a partnership with the Poplar River First Nations in association with Whelan Associates, Manitoba Wildlands, and PDK Projects, Inc. The purpose is to design approaches to study peatlands and climate change by integrating traditional knowledge with modern science. The project is also an important component of the Poplar River First Nations land management plan. The FSWRP will explore partnerships with other First Nation groups in Ontario. The main intents of these partnerships are to:

- Aid NGOs and First Nations in obtaining funds for projects to train First Nation members in soil and water data collection and working with Elders to integrate traditional ecological knowledge into the FSWRP. This is accomplished by FSWRP staff being co-principal investigators and contributing in-kind support for leveraging funds for proposal submissions.
- Train NGOs and First Nations members in soil and water sample collection and analyses to expand the number of research and monitoring sites and to provide additional databases that the FSWRP can use for validating models and predicting ecosystem processes.

Staffing

Forest Soil and Water Research Program staff include a lead scientist, program coordinator, and resource technicians. In addition, technical and graduate research positions are supported either by OMNR or partner institutions. As the program expands, individuals with expertise in remote sensing; GIS; hydrologic, carbon and soil nutrient spatial modelling; microbiology, and biochemistry will be required. These positions will likely be filled through partner organizations using external funding sources. Projected staffing and associated responsibilities required for basic program functioning over the five-year period covered by this strategy include:

Internal

- Research scientist (Jim McLaughlin): Research management including the development of strategies, proposals and delivery of science products such as publications and presentations.
- Professional staff (Sandra Wawryszyn): Program coordination, GIS, reports, partnerships, budget.
- Post-doc (TBA): Modelling support.
- Technical staff (Ted Atkinson, John Ralston): Interface with lab, field and lab coordination, quality assurance/quality control, refining protocols, field and laboratory support.
- Field/lab support (TBA): One, 6-12 month contract position for field and lab work.

External

- Additional field support: to be contracted out.
- Sample preparation: two Natural Resources Canada internships.

Program Development and Future Initiatives

The FSWRP aims to be a leader in forest soil and water research at international, national, and provincial levels. Program development is an ongoing process and program staff will continue to seek new partners and to strengthen existing partnerships and networks.

The program has a responsibility to recognize emerging issues and respond to these issues with appropriate research. Project development, program strategies, publications, and incorporation of program research in policy are key indicators of the program's progress and success. The program is well positioned to identify and transfer research needs to forest policy and industry based on continuously evolving global resource management issues. Through extensive networking and maintaining a current research framework, the FSWRP can adapt to emerging issues, while ensuring quality and integrity of existing projects and data. For example, ongoing research projects will incorporate stable isotope work and modelling framework development to position the program as a continued leader in scientific understanding of forest ecosystem functions and to produce applicable products in response to current and future management issues.

In addition to field-based research and modelling, the FSWRP is actively involved in laboratory research and development in collaboration with OFRI's geochemistry laboratory and various laboratories at Ontario universities. The focus is on developing new field-based measurement equipment that supports improved cost-effective data collection. This will bolster the program's ability to provide timely information and remain on the forefront of forest soil and water research. Towards the end of this five-year strategy we will evaluate research accomplishments, new knowledge needs, and emerging issues and update the strategy accordingly.

Technology Transfer

During the five-year period of this strategy, the technology transfer activities of the FSWRP will focus on publications, presentations, workshops, and field tours as outlined below.

Publications

- McLaughlin, J.W., S. Schiff, and M.F. Jurgensen. In review. Riparian fen organic matter decomposition controls on boreal stream alkalinity. Recent Research on Forest Ecology. Nova Science Publishers, Inc., Hauppauge, NY.
- McLaughlin, J.W. and M.F. Jurgensen. In review. Ontario peatland contributions to global carbon cycles: uncertainty analysis of carbon storage. Soil Sci. Soc. Am. J.
- Natural variability in forest soil carbon and nitrogen pools in Ontario. In preparation. Can. J. For. Res.
- Carbon balance of a southern boreal forest watershed in Ontario. Climatic Change.
- Nitrogen hydrochemistry in fen, forested, and alder riparian zones and their contribution to watershed nitrogen fluxes. Ecosystems.
- Litter fluxes and decomposition in forested and alder riparian zones in Ontario. Soil Biol. Biochem.
- Ontario peatland management: climate change, hydrology, and water quality research needs. OFRI Forest Research Information Paper.
- Long-term soil carbon and nitrogen pools after full-tree harvesting, site preparation, and regeneration. Can. J. For. Res.
- Peat carbonate and dissolved inorganic carbon stable isotope dynamics in riparian fen peatlands and streams. Biogeochemistry.

Presentations

- OFRI Management Team
- OMNR's Forest Division Joint Branch Leadership Team
- OMNR's Executive Committee
- Scientific meetings, such as the Soil Science Society of America and Canadian Soil Science Society annual meetings

Workshops

- Peatland management and climate change, 2007-2008.
- Riparian zone management: considerations for riparian management strategy 2008-2009

Field tours

- Riparian zone management 2008-2009
- Peatland management 2008-2009

Program Funding and Challenges

The FSWRP is continuously seeking both internal (OMNR) and external funding through international, federal, and provincial agencies and trusts. Existing partnerships greatly improve the competitiveness of the program in obtaining external research grants. The FSWRP also partners with the private sector in various aspects of environmental management to facilitate access to research dollars that are available only to private companies. The program will continue to use both internal and external funding to function over the next five-year period.

A number of potential threats to the sustainability of the FSWRP exist. These are:

- Lack of flexibility to proceed rapidly when emerging issues arise.
- Lack of long-term funding commitments, requiring program staff to spend a significant portion of their time writing proposals as opposed to conducting and publishing research and delivering workshops and field tours.
- Human resources issues, particularly the inability to (1) provide more than 18-month contract commitments to potential post-doctoral employees and (2) allow graduate students to conduct their research at the Ontario Forest Research Institute as members of a partner university, reducing the opportunities to access these important skill sets.
- Restrictions on out-of-province travel that hinders the ability of program staff to present results to partners and peers as well as to attend partnership meetings outside Ontario.

A multitude of soil and water issues have arisen during the past five years, all requiring rapid and innovative approaches to accomplishing research objectives within the OMNR. As such, OMNR's research programs need to remain flexible but with clear objectives and goals to ensure greater flexibility to support rapid decision-making within the OMNR. Moreover, social issues are likely to intensify as society and politicians demand more say in how natural resources will be managed. OMNR needs to understand the potential consequences of management decisions and use these outcomes to develop sound policies and innovative practices that balance ecological and environmental concerns and economic stability of northern Ontario. This will be a major challenge for the OMNR as a resource management agency within its current staffing and fiscal realities.

Literature Cited

Aherne, J., T. Larssen, B.J. Cosby and P.J. Dillon. 2006. Climate variability and forecasting surface water recovery from acidification: Modelling drought-induced sulphate release from wetlands. Sci. Tot. Environ. 365: 186-199.

Aherne, J., M. Posh, P.J. Dillon and A. Henriksen. 2004. Critical loads of acidity for surface waters in south-central Ontario, Canada: Regional application of the First-Order Acidity Balance (FAB) Model. Water Air Soil Pollut.: Focus 4: 25-36.

Aikenhead, J.A., D. Hope and M.F. Billett. 1999. The relationship between dissolved organic carbon in stream water and soil organic carbon pools at different spatial scales. Hydrol. Process. 13: 1289-1302.

Akselsson, C., J. Holmqvist, M. Alveteg, D. Kurz and H. Sverdrup. 2004. Scaling and mapping regional calculations of soil chemical weathering rates in Sweden. Water Air Soil. Pollut. Focus 4: 671-681.

Algesten, G.A., S. Sobek, A.-K. Bergstrom, A. Argen, L.J. Tranvick and M. Jansson. 2003. Role of lakes for organic carbon cycling in the boreal zone. Global Change Biol. 10: 141-147.

Andersen, L.G., P.O.J. Hall, A. Iverfeldt, M.M.R. van der Loeff, B. Sundby and S.F.G. Westerlund. 1986. Benthic respiration measured by total carbonate production. Limnol. Oceanogr. 31: 319-329.

Apps, M.J., W.A. Kurz, S.J. Beukuma and J.S. Bhatti. 1999. Carbon budget of the Canadian forest product sector. Environ. Sci. Pol. 2: 25-41.

Archibald, D.J., W.B. Wiltshire, D.M. Morris and B.D. Batchelor. 1997. Forest management guidelines for the protection of the physical environment. Ver. 1.0. Ont. Min. Nat. Resour., Toronto, ON.

Arseneault, D. 2001. Impact of fire behaviour on postfire forest development in a homogenous boreal landscape. Can. J. For. Res. 31: 1367-1374.

Aselmann, I. and P.J. Crutzen. 1989. Global distribution of natural freshwater wetlands and rice paddies, their net primary productivity, seasonality and possible methane emissions. J. Atmos. Chem. 8: 307-359.

Band, L.E., S. Mackay, I.F. Creed, R. Semkin and D. Jeffries. 1996. Ecosystem processes at the watershed scale: sensitivity to potential climate change. Limnol. Oceanogr. 41: 928-938.

Bastviken, D., J. Cole, M. Pace and L. Tranvik. 2004. Methane emissions from lakes: Dependence of lake characteristics, two regional assessments and a global estimate. Global Biogeochem. Cycles 18. doi:10.1029/2004GB002238.

Beach, E.W. and C.B. Halpern. 2001. Controls on conifer regeneration in managed riparian forests: effects of seed source, substrate, and vegetation. Can. J. For. Res. 31: 471-482.

Bell, F.W., D.G. Pitt, M. Irvine, W.C. Parker, L.J. Buse, N. Stocker, W.D. Towill, H. Chen, K. Brown, D. Deyoe, T. McDonough, G. Smith and M. Weber. 2000. Intensive forest management in Ontario: Summary of a 1999 Science Workshop. Ont. Min. Nat. Resour., Sault Ste. Marie, ON. Sci. Develop. Transf. Ser. No. 003. 86 p.

Bell, F.W., D.G. Pitt and M. Wester. 2006. Is intensive forest management a misnomer? An Ontario-based discussion of terminology and an alternative approach. For. Chron. 82: 662-674.

Berg, D.R. 1995. Riparian silvicultural system design and assessment in the Pacific northwest Cascade Mountains, USA. Ecol. Appl. 5: 87-96.

Bergeron, Y.S., Gauthier, V. Kafka, P. Lefort and D. Lesieur. 2001. Natural fire frequency for the eastern Canadian boreal forest: consequences for sustainable forestry. Can. J. For. Res. 31: 384-391.

Bhatti, J.S., M.J. Apps and H. Jiang. 2002. Influence of nutrients, disturbances and site conditions on carbon stocks along a boreal forest transect in central Canada. Plant Soil 242: 1-14.

Billett, M.F., C.M. Deacon, S.M. Palmer, J.J.C. Dawson and D. Hope. 2006. Connecting organic carbon in stream water and soils in a peatland catchment. J. Geophys. Res. 111. doi:10.1029/2005JG000065.

Billett, M.F., S.M. Palmer, D. Hope, C. Deacon, R. Storeton-West, K.J. Hargreaves, C. Flechard and D. Fowler. 2004. Linking land-atmosphere-stream carbon fluxes in a lowland peatland system. Global Biogeochem. Cycles 18. doi:10.1029/2003GB002058.

Bouchard, M. and S. Jolicoeur. 2000. Chemical weathering studies in relation to geomorphological research in southeastern Canada. Geomorphology 32: 213-238.

Bouchon, E. and D. Arseneault. 2004. Fire disturbance during climate change: failure of postfire forest recovery on a boreal floodplain. Can. J. For. Res. 34: 2294-2305.

Busse, L.L. and G. Gunkel. 2001. Riparian alder fens – source or sink for nutrients and dissolved organic carbon? – 1. Effects of water level fluctuations. Limnologica 31: 307-315.

Buttle, J.M., I.F. Creed and J.W. Pomeroy. 2000. Advances in Canadian forest hydrology, 1995-1998. Hydrol. Proc. 14: 1551-1578.

Buttle, J.M., P.J. Dillon and G.R. Eerkes. 2004. Hydrologic coupling of slopes, riparian zones and streams: an example for the Canadian Shield. J. Hydrol. 287: 161-177.

Cannell, M.G.R. and J.H.M. Thornley. 2003. Ecosystem productivity is independent of some soil properties at equilibrium. Plant Soil 257: 193-204.

Carmona, M. and E. Diaz. 2005. Iron-reducing bacteria unravel novel strategies for the anaerobic catabolism of aromatic compounds. Mol. Microbiol. 58: 1210-1215.

Clair, T.A., J.M. Ehrman and K. Higuchi. 1999. Changes in freshwater carbon exports from Canadian terrestrial basins to lakes and estuaries under 2xCO$_2$ atmospheric scenario. Global Biogeochem. Cycles 13: 1091-1097.

Cole, D.W. 1995. Soil nutrient supply in natural and managed forests. Plant Soil 168-169: 43-53.

Colombo, S.J., W.C. Parker, N. Luckai, Q. Dang and T. Cai. 2005. The effects of forest management on carbon storage in Ontario's forests. Ont. Min. Nat. Resour., Appl. Res. Devel. Br., Sault Ste. Marie, ON. Climate Change Res. Rep. CCRR-03. 126 p.

Compton, J.S. 1988. Degree of supersaturation and precipitation of organogenic dolomite. Geology 16: 318-321.

Conrad, R. 1996. Soil microorganisms as controllers of atmospheric trace gases (H_2, CO, CH_4, OCS, N_2O, and NO). Microb. Rev. 60: 609-640.

Covington, W.W. 1981. Changes in forest floor organic matter and nutrient content following clear cutting in northern hardwoods. Ecology 62: 41-48.

Cui, J., C. Li, G. Sun, and C.C. Trettin. 2005. Linkage of MIKE SHE to Wetland-DNDC for carbon budgeting and anaerobic biogeochemistry simulation. Biogeochemistry 72: 147-167.

Dale, V.H., L.A. Joyce, S. McNulty, R.P. Neilson, M.P. Ayres, M.D. Flannigan, P.J. Hanson, L.C. Irland, A.E. Lugo, C.J. Peterson, D. Simberloff, F.J. Swanson, B.J. Stocks and B.M. Wotton. 2001. Climate change and forest disturbances. BioScience 51: 723-734.

Dawson, J.J.C., M.F. Billett, D. Hope, S.M. Palmer and C.M. Deacon. 2004. Sources and sinks of aquatic carbon in a peatland stream continuum. Biogeochemistry 70: 71-82.

Dillon, P.J. and L.A. Molot. 1997. Dissolved organic and inorganic carbon mass balances in central Ontario lakes. Biogeochemistry 36: 29-42.

Duckert, D.R. and D.M. Morris. 2001. Impacts of harvest intensity on long-term site productivity in black spruce ecosystems: an establishment report. Ont. Min. Nat. Resour., Cent. North. For. Ecosys. Res., Thunder Bay, ON. CNFER Tech. Rep. TR-008. 39 p.

Dupont, J., T.A. Clair, C. Gagnon, D.S. Jeffries, J.S. Kahl, S.J. Nelson, and J.M. Peckenham. 2005. Estimation of critical loads of acidity for lakes in northeastern United States and eastern Canada. Environ. Monit. Assess. 109: 271-291.

Eckhardt, B.W. and T.R. Moore. 1990. Controls on dissolved organic carbon concentrations in streams, southern Quebec. Can. J. Fish. Aquat. 47: 1537-1544.

Einsele, G., J. Yan and M. Hinderer. 2001. Atmospheric carbon burial in modern lake basins and its significance for the global carbon budget. Global Plant. Change 30: 167-195.

Elder, J.F., N.B. Rybeck, A. Carter and V. Weintraub. 2000. Sources and yields of dissolved carbon in northern Wisconsin stream catchments with differing amounts of peatland. Wetlands 20: 113-125.

England, L.E. and D. Rosemond. 2004. Small reductions in forest cover weaken terrestrial-aquatic linkages in headwater streams. Freshwater Biol. 49: 721-723.

Environment Canada. 2004. 2004 Canadian acid deposition science assessment: Summary of key results. Environ. Can., Meteorol. Serv., Ottawa, ON. 32 p.

Ericsson, K. and L.J. Nilsson. 2004. International biofuel trade – a study of the Swedish import. Biomass Bioenergy 26: 205-220.

Fiedler, S. and K. Kalbitz. 2003. Concentrations and properties of dissolved organic matter in forest soils as affected by the redox regime. Soil Sci. 168: 793-801.

Finlay, J.C. 2003. Controls of streamwater dissolved inorganic carbon dynamics in a forested watershed. Biogeochemistry 62: 231-252.

Fischer S.G. and G.E. Likens. 1973. Energy flow in Bear Brook, New Hampshire: an integrative approach to stream ecosystem metabolism. Ecol. Monogr. 43: 421-439.

Forestry Canada. 1992. The state of Canada's forests. For. Can., Can. For. Serv., Ottawa, ON.

Frelich, L.E. and P.B. Reich. 1995. Spatial patterns and succession in a Minnesota southern-boreal forest. Ecol. Monogr. 65: 352-346.

Gleeson, J., A. Zeller and J. McLaughlin. 2006. Peat as a fuel source: A preliminary literature review. Ont. Min. Nat. Resour., Sault Ste. Marie, ON. For. Res. Info. Paper 161. 30 p.

Gorham, E. 1991. Northern peatlands: role in the carbon cycle and probable responses to climatic warming. Ecol. Appl. 1: 182-195.

Gorham, E., J.A. Janssens and P.H. Glaser. 2003. Rates of peat accumulation during the postglacial period in 32 sites from Alaska to Newfoundland, with special emphasis on northern Minnesota. Can. J. Bot. 81: 429-438.

Goodale, C.L., M.J. Apps, R.A. Birdsey, C.B. Field, L.S. Heath, R.A. Houghton, J.C. Jenkins, G.H. Kohlmaier, W. Kurz, S. Liu, G.-J. Nabuurs, S. Nilsson and Z. Shvidenko. 2002. Forest carbon sinks in the Northern Hemisphere. Ecol. Appl. 12: 891-899.

Goulden, M.L., S.C. Wofsy, J.W. Harden, S.E. Trumbore, P.M. Crill, S.T. Gower, T. Fries, B.C. Daube, S.-M. Fan, D.J. Sutton, A. Bazzaz and J.W. Munger. 1998. Sensitivity of boreal forest carbon balance to soil thaw. Science 279: 214-217.

Gower, S.T., R.E. McMurtie and D. Murte. 1996. Aboveground net primary production decline with stand age: potential causes. Trend. Ecol. Evol. 11: 378-382.

Grace, J. 2004. Understanding and managing the global carbon cycle. J. Ecol. 92: 186-202.

Guggenberger, G. and L. Kaiser. 2003. Dissolved organic matter in soils: challenging the paradigm of sorptive preservation. Geoderma 113: 293-310.

Halsey, L.A., D.H. Vitt and I.E. Bauer. 1998. Peatland initiation during the Holocene in continental western Canada. Clim. Change 40: 315-342.

Halsey, L.A., D.H. Vitt and D.O. Trew. 1997. Influence of peatlands on the acidity of lakes in northeastern Alberta, Canada. Water Air Soil Pollut. 96: 17-38.

Hamel, B., N. Belanger and D. Pare. 2004. Productivity of black spruce and jack pine stands in Quebec as related to climate, site biological features and soil properties. For. Ecol. Manage. 191: 239-251.

Hanson, P.C., A.I. Pollard, D.L. Bade, K. Predick, S.R. Carpenter and J.A. Foley. 2004. A model of carbon evasion and sedimentation in temperate lakes. Global Change Biol. 10: 1285-2298.

Harden, J.W., S.E. Trumbore, B.J. Stocks, A. Hirsch, S.T. Gower, K.P. O'Neill and E.S. Kasischke. 2000. The role of fire in the boreal carbon budget. Global Change Biol. 6(Suppl.1): 174-184.

Harper, K.A. and S.E. Macdonald. 2001. Structure and composition of riparian boreal forest: New methods for analyzing edge influence. Ecology 82: 649-659.

Hely, C., M. Flannigan, Y. Bergeron and D. McRae. 2001. Role of vegetation and weather on fire behaviour in the Canadian mixedwood boreal forest using two fire behaviour prediction systems. Can. J. For. Res. 31: 430-441.

Hemond, H.F. 1980. Biogeochemistry of Thoreau's Bog, Concord, Massachusetts. Ecol. Monogr. 50: 507-526.

Henricksen, A., P.J. Dillon and J. Aherene. 2002. Critical loads of acidity for surface waters in south-central Ontario, Canada: regional application of the Steady-State Water Chemistry (SSWC) model. Can. J. Fish. Aquat. Sci. 59: 1287-1295.

Hillring, B. 2006. World trade in forest products and wood fuel. Biomass Bioenergy 30: 815-825.

Hobbie, S.E., K.J. Nadelhoeffer and P. Hogberg. 2002. A synthesis: the role of nutrients as constraints in carbon balances in boreal and arctic regions. Plant Soil 242: 163-170.

Hobbie, S.E., J.P. Schimel, S.E. Trumbore and J.R. Randerson. 2000. Controls over carbon storage and turnover in high-latitude soils. Global Change Biol. 6(Suppl. 1): 196-210.

Hom, J. 2003. Soil carbon in permafrost-dominated boreal forests. Pp. 259-277 *in* J.M. Kimble, L.S. Heath, R.A. Birdsey, and R. Lal (eds.). The Potential of U.S. Forest Soils to Sequester Carbon and Mitigate Climate Change. CRC Press/Lewis Publishers. Boca Raton, FL.

Hope, D., S.M. Palmer, M.F. Billett and J.J.C. Dawson. 2001. Carbon dioxide and methane evasion from a temperate peatland stream. Limnol. Oceanogr. 46: 847-857.

Hornbeck, J.W. and J.N. Kochenderfer. 2000 Linkages between forests and streams: a perspective in time. Pp. 89-98 *in* E.S. Verry, J.W. Hornbeck and C.A. Dolloff (eds.). Riparian Management in Forests of the Continental Eastern United States. CRC Press/Lewis Publishers, Boca Raton, FL.

Houghton, R.A. 2003. Why are estimates of the terrestrial carbon balance so different? Global Change Biol. 9: 500-509.

Houghton, R.A., E.A. Davidson and G.M. Woodwell. 1998. Missing sinks, feedbacks, and understanding the role of terrestrial ecosystems in the global carbon balance. Global Biogeochem. Cycles 12: 25-34.

Hunt, S.L., A.M. Gordon, D.M. Morris and G.T. Marek. 2003. Understory vegetation in northern Ontario jack pine and black spruce plantations: 20-year successional changes. Can. J. For. Res. 33: 1791-1803.

Huttunen, J.T., T.S. Vaisanen, M. Heikkenen, S. Hellsten, H. Nykanen, O. Nenone and P.J. Martikainen. 2002. Exchange of CO_2, CH_4, and N_2O between the atmosphere and two northern boreal ponds with catchments dominated by peatlands or forests. Plant Soil 242: 137-146.

Hylander, K., B.G. Jonsson and C. Nilsson. 2002. Evaluating buffer strips along streams using bryophytes as indicators. Ecol. Appl. 12: 797-806.

[IPCC] International Panel on Climate Change. 2003. Good Practice Guidance for Land Use, Land-Use Change and Forestry *in J. Penman, M. Gyarsky, T. Hiraishi, T. Krug, D. Kruger, R. Pipatti, L. Buendia, K. Miwa, T. Mgara, K. Tanabe, and F. Wagner (eds.). Inst. Global Environ. Strat., Hayama, Kanagawa, Japan.*

Jacks, G. and A.-C. Norrstrom. 2004. Hydrochemistry and hydrology of forest riparian wetlands. For. Ecol. Manage. 196: 178-197.

Johnson, D.W. and P.S. Curtis. 2001. Effects of forest management on soil C and N storage: Meta analysis. For. Ecol. Manage. 140: 227-238.

Johnson, N.M., G.E. Likens, F.H. Bormann and R.S. Pierce. 1968. Rate of chemical weathering of silicate minerals in New Hampshire. Geochim. Cosmochim. Acta. 32: 532-545.

Jonsson, A., J. Kalsson and M. Jansson. 2003. Sources of carbon dioxide supersaturation in clearwater and humic lakes in northern Sweden. Ecosystems 6: 224-235.

Kalbitz, K., D. Schwesig, J. Schmerwitz, K. Kaiser, L. Haumaier, B. Glaser, R. Ellerbrock and P. Leinweber. 2003. Changes in properties of soil-derived dissolved organic matter induced by biodegradation. Soil Biol. Biochem. 35: 1129-1142.

Kasischke, E.S., N.L. Christensen, Jr. and B.J. Stocks. 1995. Fire, global warming, and the carbon balance of boreal forests. Ecol. Appl. 5: 437-451.

Kimmins, J.P. 1977. Evaluation of the consequences for future tree productivity of the loss of nutrients in whole-tree harvesting. For. Ecol. Manage. 1: 169-183.

Kling, G.W., G.W. Kipphut and M.C. Miller. 1991. Arctic lakes and streams as conduits to the atmosphere: implications for tundra carbon budgets. Science 251: 298-301.

Laiho, R., H. Vasander, T. Penttila and J. Laine. 2003. Dynamics of plant-mediated organic matter and nutrient cycling following water-level drawdown in boreal peatlands. Global Biogeochem. Cycles 17. doi:10.1029/2002GB002015.

Landsberg, J. 2003. Modelling forest ecosystems: state of the art, challenges, and future directions. Can. J. For. Res. 33: 385-397.

Lavoie M., D. Pare, and Y. Bergeron. 2005. Impact of global change and forest management on carbon sequestration in northern forested peatlands. Environ. Rev. 13: 199-240.

Layzell, D.B., J. Stephen and S. Wood. 2006. Exploring the potential for biomass power in Ontario. BIOCAP Foundation, Kingston, ON. 27 p.

Liu, J., C. Peng, M. Apps, Q. Dang, E. Banfield and W. Kurz. 2002. Historic carbon budgets of Ontario's forest ecosystems. For. Ecol. Manage. 169: 103-111.

Macdonald, E., C.J. Burgess, G.J. Scrimgeour, S. Boutin, S. Reedyk and B. Kotak. 2004. Should riparian buffers be part of forest management based on emulation of natural disturbance. For. Ecol. Manage. 187: 185-196.

MacDonald, G.B., J.A. Rice, J. McLaughlin, J. Pearce, L. Venier, K. Nystrom, and P. Meek. 2003. Developing sustainable mixedwood practices in a stand-level adaptive management (SLAM) framework. Ont. Min. Nat. Resour., Ont. For. Res. Inst., Sault Ste. Marie, ON. For. Res. Inf. Pap. No. 157. 17 p.

Malkonen, E. 1976. Effect of whole-tree harvesting on soil fertility. Silva Fennica 10: 157-164.

Margolis, H. and C. Coursolle. 2003. Fluxnet-Canada Annual Progress Report 2003. Fluxnet-Canada Network Management Office, University of Laval, Laval, QC. 145 p.

McGlynn, B.L. and J.J. McDonnell. 2003. Role of discrete landscape units in controlling catchment dissolved organic carbon dynamics. Water Resour. Res. 39: doi:10.1029/WR001525.

McGuire, A.D., J.M. Melillo and L.A. Joyce. 1995. The role of nitrogen in the response of forest net primary production to elevated carbon dioxide. Ann. Rev. Ecol. Syst. 26: 473-503.

McKnight, D., E.M. Thurman, R.L. Wershaw and H. Hemond. 1985. Biogeochemistry of aquatic humic substances in Thoreau's Bog, Concord, Massachusetts. Ecology 66: 1339-1352.

McLaughlin, J.W. 2004. Carbon assessment in boreal wetlands of Ontario. Ont. Min. Nat. Resour., Ont. For. Res. Inst., Sault Ste. Marie, ON. For. Res. Inf. Pap. No. 158. 79 p.

McLaughlin, J.W. and M.F. Jurgensen. in review. Ontario carbon budget: uncertainty analysis of peat carbon storage. Soil Sci. Soc. Am. J.

McLaughlin, J.W. and S.A. Phillips. 2006. Soil carbon, nitrogen, and base cation cycling 17 years after whole-tree harvesting a low-elevation red spruce (*Picea rubens*)-balsam fir (*Abies balsamea*) forested watershed in central Maine, USA. For. Ecol. Manage. 222: 134-253.

McLaughlin J.W., M.R. Gale, M.F. Jurgensen and C.C. Trettin. 2000. Soil organic matter and nitrogen cycling in response to harvesting, mechanical site preparation, and fertilization in a wetland with a mineral subsoil. For. Ecol. Manage. 129: 7-23.

McLaughlin, J.W., I.J. Fernandez, S.M. Goltz, L.E. Rustad and L. Zibilske. 1996a. Biogeochemical cycling of carbon, nitrogen, and sulfur at the Howland Integrated Forest Study Site, Howland, Maine. Pp. 68-77 *in* J. Hom, R. Bridsey, and K. O'Brian (eds.), Proceedings of the 1995 Meeting of the Northern Station's Global Change Program. Northeast. For. Exp. Sta., Gen. Tech. Rep. NE-214, U.S.D.A. For. Serv., Radnor, PA.

McLaughlin, J.W., G. Liu, M.F. Jurgensen and M.R. Gale. 1996b. Organic carbon characteristics in a spruce swamp five years after harvesting. Soil Sci. Soc. Am. J. 60: 1228-1236.

McLaughlin J.W., J.C. Lewin, D.D. Reed, M.R. Gale, C.C. Trettin and M.F. Jurgensen. 1994. Soil factors related to dissolved organic carbon concentrations in a black spruce swamp, Michigan. Soil Sci. 158: 454-464.

McLaughlin, J.W., S. Schiff and M.F. Jurgensen. in review. Riparian fen peatland decomposition controls on boreal stream alkalinity. Recent Research on Forest Ecology. Nova Science Publishers, Inc., Hauppauge, NY.

Merrill, A.G. and T.L. Benning. 2006. Ecosystem type differences in nitrogen process rates and controls in the riparian zone of a montane landscape. For. Ecol. Manage. 222: 145-161.

Michalzik, B., E. Tipping, J. Mulder, J.F.G. Lancho, E. Matzner, C.L. Bryant, N. Clarke, S. Lofts and M.A.V. Esteban. 2003. Modelling the production and transport of dissolved organic carbon in forest soils. Biogeochemistry 66: 241-267.

Molot, L.A. and P.J. Dillon. 1996. Storage of terrestrial carbon in boreal lake sediments and evasion to the atmosphere. Global Biogeochem. Cycles 10: 483-492.

Moore, T.R., N.T. Roulet and J.M. Waddington. 1998. Uncertainty in predicting the effect of climatic change on the carbon cycling of Canadian peatlands. Clim. Change 40: 229-245.

Morris, D.M., D.R. Duckert and B.A. Barker. 2005. Soil quality monitoring of shallow soil ecosites in northwestern Ontario: A comparison of full-tree and tree length logging – a nutrient budget approach. Ont. Min. Nat. Resour., Cent. North. For. Ecosys. Res., Thunder Bay, ON. 70 p. (http://documents.mnr.gov.on.ca/Document/View.asp?Document_ID=11436&Attachment_ID=22175; Accessed Nov 2006)

Morris, D.M., J.P. Kimmins and D.R. Duckert. 1997. The use of soil organic matter as a criterion of the relative sustainability of forest management alternatives: a modelling approach using FORECAST. For. Ecol. Manage. 94: 61-78.

Muller, A. 2003. Energy conservation in acetogenic bacteria. Appl. Environ. Microbiol. 69: 6345-6353.

Naiman, R.J. and H. Decamps. 1997. The ecology of interfaces: Riparian zones. Ann. Rev. Ecol. Syst. 28: 621-658.

Naiman, R.J., H. Decamps and M.E. McClain. 2005. Riparia: Ecology, Conservation, and Management of Streamside Communities. Elsevier Acad. Press, Amsterdam, NED. 430 p.

Nalder, I.A. and R.W. Wein. 1999. Long-term forest floor carbon dynamics after fire in upland boreal forests of western Canada. Global Biogeochem. Cycles 13: 951-968.

Neal, C. 2001. Alkalinity measurements within natural waters: towards a standardised approach. Sci. Tot. Environ. 265: 99-113.

Neff, J.C. and G.P. Asner. 2001. Dissolved organic carbon in terrestrial ecosystems: synthesis and a model. Ecosystems 4: 29-48.

Nitschke, C.R. 2005. Does forest harvesting emulate fire disturbance: a comparison of effects on selected attributes in coniferous-dominated headwater systems. For. Ecol. Manage. 214: 305-319.

Ogrinc, N., H. Hintelmann, C. Eckley, and S. Lojen. 2003. Biogeochemical influence on carbon isotope signature in boreal lake sediments. Hydrobiologia 494: 207-213.

Olsson, B.A., H. Staaf, H. Lundkvist, J. Bengtsson and K. Rosen. 1996. Carbon and nitrogen in coniferous forest soils after clear-felling and harvests of different intensity. For. Ecol. Manage. 82: 19-32.

O'Neill, K.P., E.S. Kasischke and D.D. Richter. 2002. Environmental controls on soil CO_2 flux following fire in black spruce, white spruce, and aspen stands of interior Alaska. Can. J. For. Res. 32: 1525-1541.

O'Neill, K.P., E.S. Kasischke and D.D. Richter. 2003. Seasonal and decadal patterns of soil carbon uptake and emission along an age sequence of burned black spruce stands in interior Alaska. J. Geophys. Res. 108 NO. D1: 8155, doi:10.29/2001JD000443.

[OMNR] Ontario Ministry of Natural Resources. 2001. Forest management guide for natural disturbance pattern emulation. Ver. 3.1. Ont. Min. Nat. Resour., Toronto, ON. 40 p.

[OMNR] Ontario Ministry of Natural Resources. 2003. Declaration Order Regarding MNR's Class Environmental Assessment Approval for Forest Management on Crown Lands in Ontario. MNR-71. Ont. Min. Nat. Resour., Toronto, ON. 48 p.

[OMNR] Ontario Ministry Natural Resources. 2005a. Our sustainable future: Ministry of Natural Resources strategic directions. Ont. Min. Nat. Resour., Toronto, ON. 22 p.

[OMNR] Ontario Ministry Natural Resources. 2005b. Science for our sustainable future: A science strategy for the Ontario Ministry of Natural Resources. Ont. Min. Nat. Resour., Toronto, ON. 32 p.

Palmer, S.M., D. Hope, M.F. Billett, J.J.C. Dawson and C.I. Bryant. 2001. Sources of organic and inorganic carbon in a headwater stream: evidence from carbon isotope studies. Biogeochemistry 52: 321-338.

Parikka, M. 2004. Global biomass fuel resources. Biomass Bioenergy 27: 613-620.

Parkhurst, D.L. and C.A.J. Appelo. 1999. User's guide to PHREEQC (Version 2) – A computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations. U.S. Geological Survey Wat.-Resour. Invest. Rep. 99-4259. 310 p.

Peltoniemi, M., R. Makipaa, J. Liski and P. Tamminen. 2004. Changes in soil carbon with stand age – an evaluation of a modeling method with empirical data. Global Change. Biol. 10: 2078-2091.

Peng, C., J. Liu, Q. Dang, M.J. Apps and H. Jiang. 2002. TRIPLEX: a generic hybrid model for predicting forest growth and carbon and nitrogen dynamics. Ecol. Model. 153: 109-130.

Phelps, C.D. and L.Y. Young. 1997. Microbial metabolism of the plant phenolic compounds ferulic and syringic acids under three anaerobic conditions. Microb. Ecol. 33: 206-215.

Plantinga, A.J. and R.A. Birdsey. 1993. Carbon fluxes resulting from U.S. private timberland management. Clim. Change 23: 37-53.

Powers, R.F., D.A. Scott, F.G. Sanchez, R.A. Voldseth, D. Page-Dumroese, J.D. Elioff and D.M. Stone. 2005. The North American Long-Term Soil Productivity Experiment: findings from the first decade of research. For. Ecol. Manage. 220: 31-50.

Prescott, C.E., D.G. Maynard and R. Lahio. 2000. Humus in northern forests: friend or foe. For. Ecol. Manage. 133: 23-36.

Price, J.S., B.A. Branfireun, J. M. Waddington and K.J. Devito. 2005. Advances in Canadian wetland hydrology, 1999-2003. Hydrol. Process. 19: 201-214.

Price, J.S. and J.M. Waddington. 2000. Advances in Canadian wetland hydrology and biogeochemistry. Hydrol. Process. 14: 1579-1589.

Pussinen, A., T. Karjalainen, R. Makipaa, L. Valsta and S. Kellomaki. 2002. Forest carbon sequestration and harvests in Scots pine stand under different climate and nitrogen deposition scenarios. For. Ecol. Manage. 158: 103-115.

Riley, J.L. 1994. Peat and peatland resources of northeastern Ontario. Ont. Geol. Surv. Sudbury, ON. Misc. Pap. 153: 155 p.

Riley, J.L. and L. Michaud. 1987. Peat and peatland resources of northwestern Ontario. Ont. Geol. Surv. Toronto, ON. Open File Rep. 5632: 275 p.

Roulet, N.T. 2000. Peatlands, carbon storage, greenhouse gases, and the Kyoto Protocol: prospects and significance for Canada. Wetlands 20: 605-615.

Rudd, J.W.M., R.D. Hamilton and N.E.R. Campbell. 1974. Measurement of microbial oxidation of methane in lake water. Limnol. Oceanogr. 19: 519-524.

Schiff, S., R. Aravena, E. Mewhinney, R. Elgood, B. Warner, P. Dillon and S. Trumbore. 1998. Precambrian shield wetlands: hydrologic control of the sources and export of dissolved organic matter. Clim. Change 40: 167-188.

Schink, B. 1997. Energetics of syntrophic cooperation in methanogenic degradation. Microb. Mol. Biol. Rev. 61: 262-280.

Schink, B. and P.P.J. Muller. 2000. Anaerobic degradation of phenolic compounds. Naturwissenschaften 87: 12-23.

Schlesinger, W.H. 1977. Carbon balances in terrestrial detritus. Ann. Rev. Ecol. Syst. 8: 51-81.

Siegel, D.I., P.H. Glaser, J. So and D.R. Janecky. 2006. The dynamic balance between organic acids and circumneutral groundwater in a large boreal peat basin. J. Hydrol. 320: 421-431.

Stocks, B.J., M.A. Fosberg, T.J. Lynham, L. Mearns, B.M. Wotton, Q. Yang, J.-Z. Jin, K. Lawrence, G.R. Hartley, J.A. Mason and D.W. McKenney. 1998. Climate change and forest fire potential in Russian and Canadian boreal forests. Clim. Change 38: 1-13.

Switzer, G.L. and L.E. Nelson. 1972. Nutrient accumulation and cycling in loblolly pine (*Pinus taeda* L.) plantation ecosystems: the first twenty years. Proc. Soil Sci. Soc. Am. 36: 143-147.

Szaran, J. 1998. Carbon isotope fractionation between dissolved and gaseous carbon dioxide. Chem. Geol. 150: 331-337.

Szramek, K. and L.M. Walter. 2004. Impact of carbonate precipitation on riverine inorganic carbon mass transport from a mid-continent forested watershed. Aquat. Geochem. 10: 99-137.

Tabacchi, E., D.L. Correll, R. Hauer, G. Pinay, A.-M. Planty-Tabacchi and R.W. Wissmar. 1998. Development, maintenance and role of riparian vegetation in the river landscape. Freshwater Biol. 40: 497-516.

Tarnocai, C.T. 1998. The amount of carbon in various soil orders and ecological provinces in Canada. Pp. 81-92 *in* R. Lal, J.M. Kimble, R.F. Follett, B.A. Stewart (eds.) Soil Processes and the Carbon Cycle. CRC Press, Boco Raton, FL. 609 p.

Telmer, K. and J. Veizer. 1999. Carbon fluxes, pCO_2 and substrate weathering in a large northern river basin, Canada: carbon isotope perspectives. Chem. Geol. 159: 61-86.

Timoney, K.P., G. Peterson and R. Wein. 1997. Vegetation development of boreal riparian communities after flooding, fire, and logging, Peace River, Canada. For. Ecol. Manage. 93: 101-120.

Tipping, E., M. Frobgerg, D. Berggren, J. Mulder and B. Bergkvist. 2005. DOC leaching from a coniferous forest floor: modeling a manipulation experiment. J. Plant Nutr. Soil Sci. 168: 316-324.

Tremblay, A., L. Varfalvy, C. Roehm, and M. Garneau (eds.). 2005. Greenhouse Gas Emissions – Fluxes and Processes: Hydroelectric Reservoirs and Natural Environments. Springer, Amsterdam, NED. 732 p.

Trettin, C.C. and M.F. Jurgensen. 2003. Carbon cycling in wetland forest soils. Pp. 311-331 *in* J.M. Kimble, L.S. Heath, R.A. Birdsey, and R. Lal (eds.). The Potential of U.S. Forest Soils to Sequester Carbon and Mitigate Climate Change. Chapter 19. CRC Press/Lewis Publishers, Boca Raton, FL.

Trettin, C.C., M.F. Jurgensen, M.R. Gale and J.W. McLaughlin. 1995. Soil carbon in northern forested wetlands: Impacts of silvicultural practices. Pp. 437-461 *in* W.W. McFee and J.M. Kelly (eds.). Carbon Form and Function in Forest Soils. Soil. Sci. Soc. Am., Madison, WI.

Trettin, C.C., M.F. Jurgensen, J.W. McLaughlin and M.R. Gale. 1997. Effects of forest management on wetland functions in a sub-boreal swamp. Pp. 411-428 *in* C.C. Trettin, M.F. Jurgensen, D.F. Grigal, M.R. Gale, and J. Jeglum (eds.). Northern Forested Wetlands: Ecology and Management. Chapter 29. CRC/Lewis Publishers, Boca Raton, FL.

Trettin, C.C., R. Laiho, K. Minkkinen and J. Laine. 2006. Influence of climate change factors on carbon dynamics in northern forested peatlands. Can. J. Soil. Sci. 86: 269-280.

Trettin, C.C., B. Song, M.F. Jurgensen and C. Li. 2001. Existing soil carbon models do not apply to forested wetlands. U.S.D.A. For. Serv., South. Res. Sta., Ashville, NC. Gen. Tech. Rep. SRS-46. 10 p.

Turetesky, M.R. and S. Ripley. 2005. Decomposition in extreme-rich fens of boreal Alberta, Canada. Soil Sci. Soc. Am. J. 69: 1856-1860.

[UNECE] United Nations Economic Commission for Europe. 2004. Handbook for the 1979 convention on long-range transboundary air pollution and its protocols. UNECE Infor. Unit, Geneva, Switzerland. 324 p.

[UNFCCC] United Nations Framework Convention on Climate Change. 1998. Report of the conference of the parties on its third session, held at Kyoto from 1 to 11 December 1997. Part Two: action taken by the Conference of Parties at its third session. FCCC/CP/1997/7/Add.1. 60 p.

Vardy, R.W., B.G. Warner, J. Turunen and R. Aravena. 2000. Carbon accumulation in permafrost peatlands in the Northwest Territories and Nunavut, Canada. The Holocene 10: 273-280.

Verry, E.S. and C.A. Dolloff. 2000. The challenge of managing for healthy riparian areas. Pp. 23-42 *in* E.S. Verry, J.W. Hornbeck, and C.A. Dolloff (eds.), Riparian Management in Forests of the Continental Eastern United States. CRC Press/Lewis Publishers, Boca Raton, FL.

Vile, M.A., S.D. Bridgham, R.K. Wieder and M. Novak. 2003. Atmospheric sulphur deposition alters pathways of gaseous carbon production in peatlands. Global Biogeochem. Cycles 17. doi:10.1029/2002GB001966.

Waddington, J.M., K.D. Warner and G.W. Kenedy. 2002. Cutover peatlands: a persistent source of atmospheric CO_2. Global Biogeochem. Cycles 16: 10.1029/2001GB001398.

Walberger, A.M., D. Le Roy, K.K. Kaushik and K.K. Klein. 2006. Policies to stimulate biofuel production in Canada: lessons from Europe and the United States. BIOCAP Foundation, Kingston, ON. 63 p.

Wallace, J.B., S.L. Eggert, J.L. Meyer and R.R. Bebster. 1999. Effects of resource limitation on a detrital-based ecosystem. Ecol. Monogr. 69: 409-442.

Weetman, J.F. and B. Webber. 1972. The influence of wood harvesting on the nutrient status of two spruce stands. Can. J. For. Res. 2: 351-369.

Welsch, D.L. and G.M. Hornberger. 2004. Spatial and temporal simulation of soil CO_2 concentrations in a small forested catchment in Virginia. Biogeochemistry 71: 415-436.

Wilson, C.A., R.J. Mitchell, L.R. Boring and J.J. Hendricks. 2002. Soil nitrogen dynamics in a fire-maintained forest ecosystem: results over a 3-year burn interval. Soil Biol. Biochem. 34: 679-689.

Wirth, C., E.-D. Schulze, B. Luhker, S. Grigoriev, M. Siry, G. Hardes, W. Ziegler, M. Backor, G. Bauer and N.N. Vygodskaya. 2002. Fire and site type effects on the long-term carbon and nitrogen balance in pristine Siberian Scots pine forests. Plant Soil 242: 41-63.

Worrall, R., T. Burt and J. Adamson. 2005. Fluxes of dissolved carbon dioxide and inorganic carbon from an upland peat catchment: implications for soil respiration. Biogeochemistry 73: 515-539.

Yanai, R.D., W.S. Currie and C.L. Goodale. 2003. Soil carbon dynamics after forest harvest: an ecosystem paradigm reconsidered. Ecosystems 6: 197-212.

Yarie, J. 2000. Boreal forest ecosystem dynamics: I. A new spatial model. Can. J. For. Res. 30: 998-1009.

Zetterberg, R., S. Uppenberg and M. Ahman. 2004. Climate impact from peat utilization in Sweden. Mitig. Adaptat. Strateg. Glob. Chang. 9: 37-76.

Zhang, Y., C. Li, C.C. Trettin, H. Li and G. Sun. 2002. An integrated model of soil, hydrology, and vegetation for carbon dynamics in wetland ecosystems. Global Biogeochem. Cycles 16. doi:10.1029/2001/GB001838.

Zhou, X., C. Peng and Q. Dang. 2004. Assessing the generality and accuracy of the TRIPLEX model using in situ data of boreal forests in central Canada. Ecol. Model. Software 19: 35-46.

Appendix I.

Workshop Overview, Participants, and Agenda

Workshop title: *Integrating OMNR Research Priorities and Climate Change: Soil and Water Resources Workshop February, 2005.*

The text below is what was provided to workshop participants in advance of the session.

Integrating climate change into forest management strategies is an important but complex concept necessary to ensure forest sustainability and the competitiveness of Ontario's forest industry in today's global economy and for the foreseeable future. Responding to this new horizon of forest management decision-making requires an enhanced understanding of forest processes and how those processes are affected by climate change, various silvicultural interventions, and their interactions with each other and climate change, over and above our current capacity. A major obstacle in developing and refining forest management decision frameworks within the Area of the Undertaking under the Ontario's Forest Class Environmental Assessment is the enormous spatial and temporal variability in soil and water properties in forested landscapes and their contributions to uncertainty in forest functions.

A major challenge in developing and applying research to support sustainable forest management decision frameworks is that 40% of the land base consists of interconnected forest, wetland, and freshwater (streams, lakes) ecotones. Thus, natural (e.g., fire) and anthropogenic disturbances (e.g., harvesting, regeneration) can result in cascading and cumulative effects on various hydro-chemical processes within a forested landscape that may negatively affect ecosystem health and forest productivity. These disturbances may also change the carbon and nitrogen sink potential of forests, resulting in increased trace gas (i.e., CO_2, CH_4, N_2O) emissions to the atmosphere, which may in turn affect local, regional, and global climate. Developing sustainable management schemes within the Area of the Undertaking requires a thorough understanding of soil and water properties. This improved understanding should improve the capacity to predict the outcomes of interactions between climate change and forest management on water, energy, and nutrient fluxes across ecotones.

Developing a strategy that integrates climate change into the current Ontario Ministry of Natural Resources (OMNR) research and management priorities, such as natural disturbance pattern emulation (NDPE), enhanced forest productivity (EFP), and riparian management under changing climatic conditions, will be challenging at several levels. One challenge is that climate change predictions based on global climate models (GCMs) for Ontario are not uniform across the province. For example, northwestern Ontario is predicted to have warmer, drier summers and winters with more frequent and intensive precipitation events in the summer. In contrast, GCM predictions for northeastern Ontario are wetter summers and either cooler temperatures or no temperature changes, increased snowfall, and delayed spring. In addition, Ontario has increased the emphasis on landscape management under the NDPE guide.

Within this multilayered set of issues, this working session will address the question "How can climate change, EFP, and riparian management be incorporated into NDPE at the watershed-scale in Ontario?" The first step in accomplishing this task is to identify the state-of-the-knowledge and the knowledge gaps about how the interactions of temperature, moisture, and vegetation structure regulate carbon, nitrogen, and water cycling and fluxes at the biosphere/atmosphere interface.

Goal

To develop a research strategy for soil/water research program that integrates climate change, enhanced forest productivity, and riparian management into natural disturbance emulation patterns at the watershed scale.

Objective

To define uncertainties and knowledge gaps for each component (climate change, enhanced forest productivity, riparian management) and the challenges faced to incorporate the components into an integrated research program.

Product

A research strategy focussed on knowledge gaps and uncertainties associated with hydro-chemical processes at watershed scales that will provide improved science to support OMNR's forest management policies within the Area of the Undertaking. This will be presented in an OFRI report, to which all working session participants are invited to contribute.

Questions for breakout group discussions

The session will focus on the following topics and associated suggested discussion questions. We will use a brainstorming approach to see if the answer is known/available given current information, and if it is unknown, suggest possible research strategies to get the answers:

Group 1: Terrestrial (Breakout sessions #1 and 2)

1. How do carbon and water cycle through watersheds?

Upland

- Are upland forests in Ontario net carbon (C) sinks or sources?
- What are the threshold climatic, environmental, and successional conditions that regulate carbon sink/source strength?
- How does depth to impermeable layers (e.g., dense till, bedrock) function to control evapotranspiration (ET), summer soil moisture deficit, and water flux to riparian systems? How do these controls interact with species composition through canopy architecture and rooting strategies?

Group 2: Riparian and Aquatic (Breakout sessions #1 and 2)

1. How do carbon, nutrients, and water cycle through riparian zones, peatlands, and surface water bodies?

Peatlands and riparian zones

- Are Ontario's peatlands a net carbon sink or source?
- What are the threshold climatic, environmental, and successional conditions that regulate carbon sink/source strength? Are these the same for different peatland types?
- What is the role of riparian nitrogen-fixing vegetation (i.e., *Alnus* spp. and *Myrica* spp.) in CO_2, CH_4, and N_2O cycling and soil carbon sequestration?
- How do soil moisture and organic matter changes affect trace gas cycling and flux?

Surface water bodies

- How is carbon and nitrogen cycled in surface waters?
- What is the role of surface sediments to trace gas flux to the atmosphere and to the presence in the water column of carbon and nitrogen organic and inorganic compounds?
- What is the role of internal carbon production versus external carbon input in affecting surface water trace gas flux?
- What is the role of aquatic vegetation in CO_2 exchange at the surface water/atmosphere interface, especial for streams that are not under canopy cover in both "natural" and disturbed areas?

Group 1. Enhanced Forest Productivity (used to be Intensive Forest Management) (Breakout session #3)

- How do we match silvicultural interventions under EFP to a watershed?
- Where on the watershed should EFP be implemented?
- How much area of a watershed can be placed into EFP?
- How do different silvicultural strategies under EFP affect soil carbon and nitrogen cycling?
- Can EFP be used to enhance forest carbon sink potential?
- How do different regeneration strategies affect organic matter quality and carbon and nitrogen cycling?
- How does mixedwood management and species shifts (i.e., conversion to conifers) affect organic matter quality and C sequestration?

Group 2. Riparian management (Breakout session #3)

- What are the major disturbance types for different riparian types?
  - Lowlands
  - Uplands
- How do we define sensitive riparian areas?
  - Hydrological responses
  - Chemical responses
  - Physical responses
- What is the role of sensitive discharge areas in maintaining stream base-flow? How can sensitive discharge areas be impacted by forest harvesting and climate change?
- How do we design riparian structure within a watershed?
- How do we develop ecologically-driven watershed management strategies?

Both Groups (if time permits)

- The intent is to use the Natural Disturbance Pattern Emulation Guide to integrate the above topics and design associated research strategies that factor in predicted climate change scenarios and their effectsUltimately, the goal is to determine the types of spatial modelling efforts required to scale the outcomes of the above strategies.

Workshop participants, organization, and area of expertise.

Name	Affiliation	Areas of Expertise
Jim McLaughlin	OMNR-OFRI	Carbon cycling
Bill Parker	OMNR-OFRI	Forest regeneration and eco-physiology
Steve Colombo	OMNR-OFRI	Forest regeneration and carbon budgeting
Rongzhou Man	OMNR-OFRI	Silviculture and regeneration
Robert Mackereth	OMNR-CNFER	Aquatic ecology
Dave Morris	OMNR-CNFER	Forest stand ecology and soil nutrient cycling
Gordon Kayahara	OMNR-NESI	Silviculture and soil nutrients
Robert Metcalf	OMNR-Watershed Science Centre	Hydrology
James Buttle	Trent University	Hydrology
Harry McCaughey	Queens University	Atmospheric physics
Paul Hazlett	CFS-GLFC	Carbon and nutrient cycling
Steve Holmes	CFS-GLFC	Ornithology
Carl Trettin	US Forest Service	Wetland ecology, carbon cycling, and hydrology
Susan Wood	BIOCAP Foundation	Building national research networks
Sandra Wavryszyn	OMNR-OFRI	Quality assurance/quality control
Bill Cole	OMNR-OFRI	Facilitator
Maara Packalen	OMNR-OFRI	Facilitator
Ted Atkinson	OMNR-OFRI	Facilitator

Workshop agenda

Integrating OMNR Research Priorities and Climate Change: Soil and Water Resources Workshop
Holiday Inn, Sault Ste. Marie, Ontario
Workshop Agenda

Day 1 -- Tues Feb 15

8:30–9:00	Coffee	
9:00–9:15	Welcome and introductions	Jim McLaughlin, OFRI
9:15–9:30	Workshop objectives and format	Facilitators
9:30–10:00	OMNR context: Priorities/issues associated with climate change, enhanced forest productivity, and riparian management as related to watershed management	Jim McLaughlin, OFRI
10:00–10:30	Does climate change affect MNR's research needs on ecological processes?	Steve Colombo, OFRI
10:30 – 10:45	Break	
10:45–11:30	Keynote – Climate change management issues and associated research needs	Harry McCaughey, Queen's University
11:30–12:15	Keynote – Wetlands management issues and associated research needs	Carl Trettin, US Forest Service
12:15–1:00	Lunch (provided)	
1:00–2:30	Break out discussions #1	All
2:30 – 2:45	Break	
2:45–3:30	Break out discussions #2	All
3:30–4:30	Reports and discussion	All
4:30–5:00	Synthesis – messages, gaps, needs	All
6:00	Dinner (provided)	

Day 2 -- Weds Feb 16

9:00 - 9:15	Welcome and objectives for Day 2	Jim McLaughlin, OFRI
9:15–10:00	Keynote – Hydrology	Jim Buttle, Trent University
10:00 - 10:15	Break	
10:15 - 12:00	Break out discussions #3	All
12:00 - 1:00	Lunch (provided)	
1:00 - 2:30	Reports and discussion	All
2:30 - 2:45	Break	
2:45 - 4:00	Research strategy and design	All
4:00 - 4:30	Synthesis – discuss roles in products, next steps	All

Appendix II.

Research priority areas based on the results of breakout group discussions at Integrating OMNR Research Priorities and Climate Change: Soil and Water Resources Workshop February, 2005.

Group	Question	Priority Areas Identified
Terrestrial	How do carbon and water cycle through watersheds?	• Need data for models • Identify appropriate models to use with the corresponding data • Identify stand-level carbon budgets • More data required for modelling belowground processes
	What are the threshold climatic, environmental, and successional conditions that regulate carbon sink/source strength?	• Require more climate data • Compare stand- versus landscape-level data • Identify what data to use for different areas
	How does depth to impermeable layers function to control evapotranspiration, summer moisture deficit, and water flux to riparian systems?	• Good knowledge base but lack data on belowground processes • Need more information on stand-level soil data • Existing growth and yield data are available for use
	How do these interact with species composition through canopy architecture and rooting strategies?	• Multiple datasets at multiple levels hinders data integration
	How does silviculture affect soil carbon and nitrogen cycling?	• What are the impacts of coarse woody debris removal under intensive forest management? • What is the organic matter storage capacity and its contributions?
Riparian, aquatic, and peatland	Are Ontario's peatlands a net sink or source of carbon?	• Need clearer indication of whether a peatland is a source or sink • What empirical data are required? • Identify carbon cycling and fluxes in different ecotones • More data on methane cycling and fluxes • Soil and landform data
	What are the threshold climatic, environmental, and successional conditions that regulate carbon source/sink strength? Are these the same for different peatland types?	• Data information for different ecotones • Share data and increase the data transfer between projects, programs, and institutions • More peatland data needs to be synthesized to understand the differences and similarities within regions and under various management regimes
	How does soil moisture and organic matter changes affect trace gas cycling and flux?	• Understanding of multi-factors is poor (e.g., modelling)
	How are carbon and nitrogen cycled in water?	• Sources of uncertainty: (i) disturbance on upstream sites, (ii) carbon balance (inputs versus outputs), gas exchange • Introduction of exotic species • Should sensitivity or ecological processes within complex cycles be measured?
	What are the major disturbance types for different riparian zones?	• Improved definitions of wetland, riparian zone, and buffer • Multifactoral riparian classification systems based on slope, topography, soil depth, geomorphology, and vegetation • Spatial and temporal scaling of disturbance types

52085
(0.3k P.R. 07 04 01)
ISSN 0319-9118
ISBN 978-1-4249-4039-4 (Print)
ISBN 978-1-4249-4040-0 (PDF)